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INVESTIGATION OF ADVANCED AIRCRAFT PERFORMANCE MEASURES OF MERIT INCLUDING NEW AGILITY METRICS

THESIS

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September 1991 Master's Thesis

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Aircraft Performance, Performance Metrics, Agility Metrics, Torsional Agility, Axial Agility, Pitch Agility 124

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INVESTIGATION OF ADVANCED AIRCRAFT PERFORMANCE MEASURES OF MERIT INCLUDING NEW *AGILITY* METRICS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

Bruce A. Fox, B.S.A.A.E.

September 1991

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List of Nomenclature

AA	–	Eidetics' Axial Agility
AFFTC	–	Air Force Flight Test Center
ALT	–	altitude
$\mathbf{A^{*}_{l.a.t.}}$	–	Dorn's large amplitude task agility
CCT	–	Kalviste's combat cycle time
$\mathbf{C_D}$	–	drag coefficient
$\mathbf{C_{Do}}$	–	drag coefficient at zero lift
$\mathbf{C_{DSB}}$	–	drag coefficient due to speed brake
$\mathbf{C_L}$	–	lift coefficient
$\mathbf{C_{Lmax}}$	–	maximum lift coefficient
DST	–	McAtee's dynamic speed turns
DT	–	Kalviste's point and shoot parameter
EA	–	Dorn's energy agility
$\mathbf{F_N}$	–	net propulsive thrust
g–level	–	wind [illegible] normal load factor
$\mathbf{h_e}$	–	specific energy
ITR	–	instantaneous turn rate

KCAS - knots calibrated airspeed

LWF - light weight fighter

M - mach number (M#)

MAX A/B - maximum thrust with afterburner

MIL PWR - military rated thrust (no time limit)

MITR - maximum instantaneous turn rate

MSTR - maximum sustained turn rate

N_Z - wind axis normal load factor (L/W)

PA - Eidetics' pitch agility

P_S - specific excess power

RPM - revolutions per minute

S - wing area

SEP - specific excess power

STR - sustained turn rate

T - net propulsive thrust

TA - Eidetics' torsional agility

t_o - initial time

t_k - time to complete task

$t_{k/r}$ - time to complete task and recover initial energy

T_{steer} - minimum time to complete 180 degree level turn

TRAJ - trajectory

T_{roll} - minimum time to bank 90 degrees about the velocity vector

TR - turn rate

T/W - thrust to weight ratio

USAFTPS - United States Air Force Test Pilot School

V_C - corner velocity

V_T - true velocity (V)

V/Vc - relative energy state

WT - aircraft weight (W)

WVR - within visual range

W/S - wing loading

α - angle of attack

γ - flight path angle

ψ - heading angle

ρ - air density

1G - acceleration equal to 32 ft/sec^2

3-DOF - three degrees of freedom

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Abstract

Advanced aircraft performance measures of merit have been proposed and individually analyzed by various researchers. These metrics have been consolidated into a single computer code as part of this research effort. This code was used to study the relationships between the advanced metrics, aircraft design metrics and an aircraft's trajectory performance.

The study found a linear relationship existed between the advanced metrics and the design metrics. This relationship was used to quantify the required levels of the advanced metrics which would give desired changes in trajectory performance. The results showed that advanced metrics could be applied only to very specific trajectory maneuvers. Thus limiting their utility in determining an aircraft's overall combat effectiveness.

INVESTIGATION

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I. Introduction

Background

Historically, within visual range air-to-air combat has been dominated by aircraft which pilots describe as being quick, nimble and very agile. These qualities, which seem to be self-evident in their description of superior aircraft, have long evaded a thorough technical definition.

For many years, successful aircraft designs have evolved using the classical aircraft performance measures of merit such as thrust to weight ratio (T/W), wing loading (W/S), corner velocity (Vc), maximum instantaneous turn rate (MITR) and specific excess power (SEP). However, according to Skow (16:3-15), a review of air combat lessons has shown that the outcome of many air-to-air engagements from WWI to the present are not fully predicted by tactics, weapons and classic performance metrics but is in part influenced by the transient performance of the individual aircraft. In recent years, technology advances such as all aspect missiles, fly-by-wire flight control systems and control configured fighter designs, have emphasized the influence of an aircraft's transient performance on combat effectiveness (7:23.1). Thus, it seems an aircraft's transient performance must be quantified in order to give a more thorough insight into the aircraft's combat effectiveness.

The problem was partially solved in the late 1970's with the advent of ground based simulators which could adequately model the transient qualities of aircraft and could be used to determine characteristic flying qualities and make estimates of the aircraft's combat effectiveness. For example, Mitchell (12) showed that the use of these simulators were very beneficial in design studies such as the unorthodox control force fighter design and also in the search for metrics which could possibly give insight to the transient performance definition. Two *agility* parameters were defined in his report which depend on the aircraft aerodynamic, inertial and propulsion data. The report suggest that these parameters may be effective in the prediction of an aircraft's combat effectiveness. These parameters are T_{steer} and T_{roll}. T_{steer} is defined as the minimum time to complete a 180 degree level turn and T_{roll} is the minimum time to bank 90 degrees about the velocity vector (12:22–26). Even though evidence of the merit of these parameters was presented in the report, the parameters have not yet been accepted by the aeronautic community.

The problem of establishing any parameter as a significant transient performance metric has recently been recognized by government agencies (DOD, NASA, DARPA) and the aircraft industry, and is currently the subject of much research. The goal of this research is to establish a set of metrics which could be used industry wide in aircraft design. Some of this research effort has been summarized in a paper by Dorn (3), the results of which are shown in Figure 1.

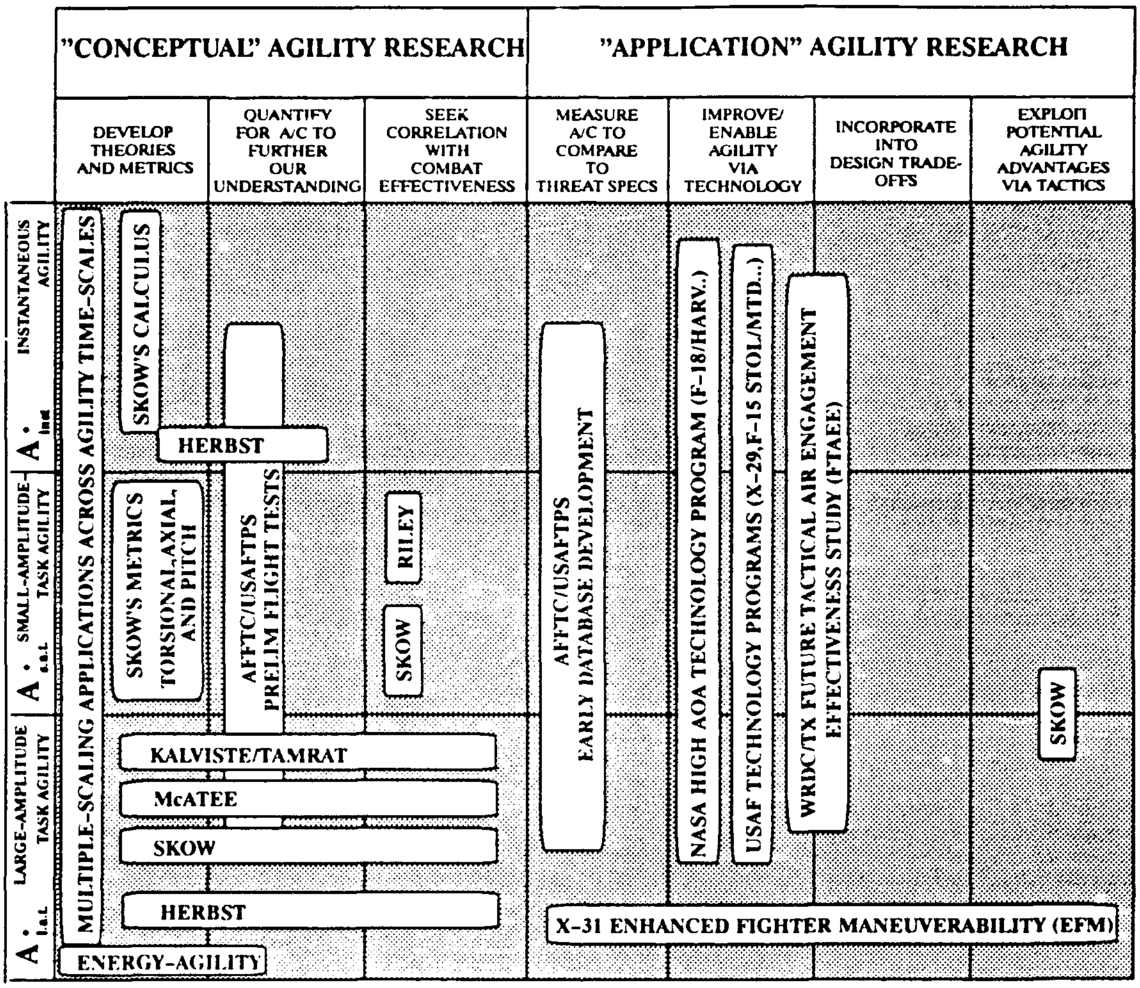


Figure 1. A View of the Current Metrics Research Effort (5:9)

Figure 1 reflects Dorn's (5:8) view of the current research activity and funding level with respect to his "three time scales of agility". The research framework shown in Figure 1 provides a useful guide to where work has been initiated and where future projects should direct their effort. It is apparent from Figure 1 that only the flight test community (AFFTC, USAFTPS) is currently investigating the group of metrics which make up the "three time scales of agility". The main goal of their investigation is to measure, via flight test, the component quantities which make up the individual metrics.

Problem Statement

To date, no effort has been placed in analytically collecting, quantifying and comparing the set of metrics which have been proposed by the individual researchers as identified in Figure 1.

Research Objectives

In light of the deficiency in an analytical comparison of the metrics as a whole, the first objective of this research was to develop computer algorithms which could be used to evaluate and quantify each metric. The second objective was to correlate the *agility* metrics and trajectory performance with some traditional design metrics, such as T/W and W/S. The third objective was to determine the sensitivity of an aircraft's flight path trajectory performance with respect to the *agility* and design metrics.

Scope/Limitations

The research effort, which is presented in the following chapters, was only directed at the metrics proposed by the individuals who have been identified in Figure 1. Their metrics are presented and the supporting arguments are given. The approach taken for this study explores the intent of each metric and displays the results in alternate formats.

Assumptions

The aircraft model used in this research, which is described in Chapter 2, is a simplified wind axis based representation of a light weight fighter (LWF) design. This model tries to encompass the various typical trends in aerodynamics and installed engine performance. The inertial rates such as roll, pitch and engine spool, which have been modeled and used in the trajectory simulations, are intended to be representative of current light weight fighter designs.

The trajectory simulation program is a 3-DOF ($\dot{V}, \dot{\gamma}$, and $\dot{\psi}$), point mass, time-step integration computer program. It uses a flat, non-rotating Earth model with a 1962 U.S. Standard Atmosphere (13) with no winds. The program allows for user defined inputs of roll angle or roll rate, g-level or g-onset rate and power level or rate. These inputs allow the user to determine the required inertial characteristics which will yield desired trajectories. The modeled trajectories which were used in this study were chosen to be representative of short, simple air combat maneuvers.

Summary of Current Knowledge

The descriptions and arguments which are presented in this section are the current attempts at defining metrics for transient performance. These definitions are generally categorized as *agility* metrics. These metrics can be classified as either analytical or experimental (5:2). The analytical metrics are typically mathematical manipulations of the governing equations of motion, whereas the experimental metrics result from trajectory simulation or actual flight tests.

The *agility* metrics described herein have been categorized according to their characteristic time-scales as shown in Figure 1. These categories: instantaneous agility, small-amplitude task agility, and large-amplitude task agility, are characterized by time-scales of 0–1, 1–2, 10–20 seconds, respectively (5:3). This summary presents the metrics and researchers in this order and will also provide references to quantification work that has been accomplished to date.

The instantaneous agility category is based on the mathematical differentiation of the governing equations of motion. Herbst identifies agility relations which result from the second inertial time derivative of the velocity vector as shown in Equation 1 and the angle definitions as shown in Figure 2.

$$\frac{{}^{I}d^2\overline{V}}{dt^2} = (\ddot{v} - v\omega^2)\hat{i}_w + (2\dot{v}\omega + v\dot{\omega})\hat{j}_w + [v\omega(Z - \dot{\chi}\sin\gamma)]\hat{k}_w \quad (1)$$

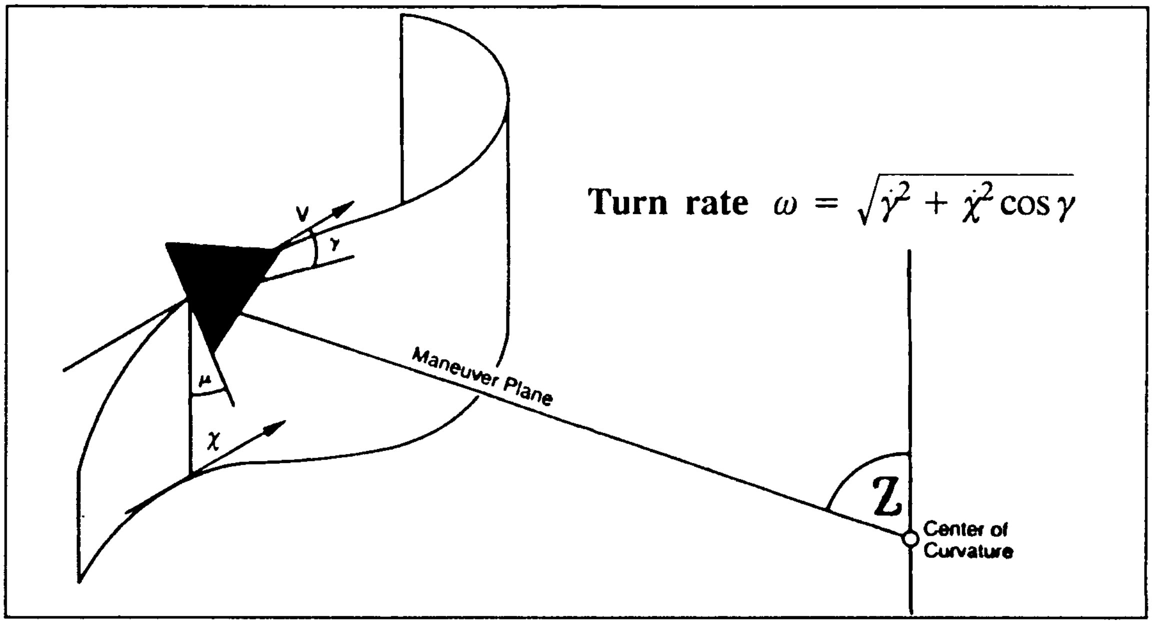


Figure 2. Definition of Problem Geometry (8:29)

Quantification work of this metric has been published by Britten (2) which shows that the metric can be used to relate the aircraft design parameters to agility.

The second category, small-amplitude task agility, is dominated by Eidetic's (Skow) metrics which are referred to as torsional, axial and pitch agility (16:29–41). These metrics are shown here as Equations 2, 3 and 4, respectively.

$$TA = \frac{\dot{\psi}}{\Delta t_{rc90^\circ}} \quad (2)$$

$$AA = \frac{(P_{s_{max}} - P_{s_{min}})}{\Delta t_{trans}} \tag{3}$$

$$PA = \Delta t_{capt\theta} \tag{4}$$

The torsional agility, as defined in Equation 2, is described as the ability to do a loaded roll maneuver. This metric combines the classic turn rate metric with a task oriented time (time to bank 90 degrees and stop). This metric, in essence, tends to separate aircraft which have similar turn rate performance but different loaded roll capability. Quantification work has been published on this metric (2;4;13) and flight tests are currently underway by AFFTC and USAFTPS. Several studies have been published by USAFTPS which have reported limited success in measurement of this metric due to problems with flight test maneuvers and instrumentation (1;3;15).

Axial agility, Equation 3, is described as the aircraft's ability to change its power state. This metric is defined as the difference between the maximum specific excess power and the minimum specific excess power divided by the time to transition between these two states. This transition time is the larger of either engine spool time or speed-brake deployment time (16:32-36). Quantification work on this metric is currently on going with Skow and the AFFTC. The only published results are from Skow (13) and USAFTPS (1). The USAFTPS reported limited success in measuring this metric due to the execution of the flight test maneuver. The main problem was that the test points were spaced too closely together, which did not allow for complete engine spool transition (1:19).

Pitch agility, as shown in Equation 4, is nothing more than the time required to capture and hold a desired pitch attitude (16:29). Quantification of this metric

is on going by Skow, AFFTC and USAFTPS. Published results are by Skow (13) and USAFTPS (3;15).

The third category, large-amplitude task agility, is dominated by the experimental class of metrics. This category consist of the results, presented in various forms, of trajectory simulations or flight test. These simulations are based on flying a maximum performance, coordinated, level turn for various initial and final conditions.

The metrics developed by Kalviste and Tamrat are the point and shoot parameter (DT), the relative energy state (V/Vc) and the combat cycle time (CCT) (9; 18). The point and shoot parameter defined by a simple equation as shown in Figure 3, quantifies an aircraft's ability to make level turns. This metric can be readily quantified using simple trajectory simulation software and trimmed aerodynamic and propulsion data. Two formats for displaying the resultant data have been suggested and are shown in Figures 4 and 5. Recent works to quantify the DT metric have been published by Cannon (4) and Kalviste (9).

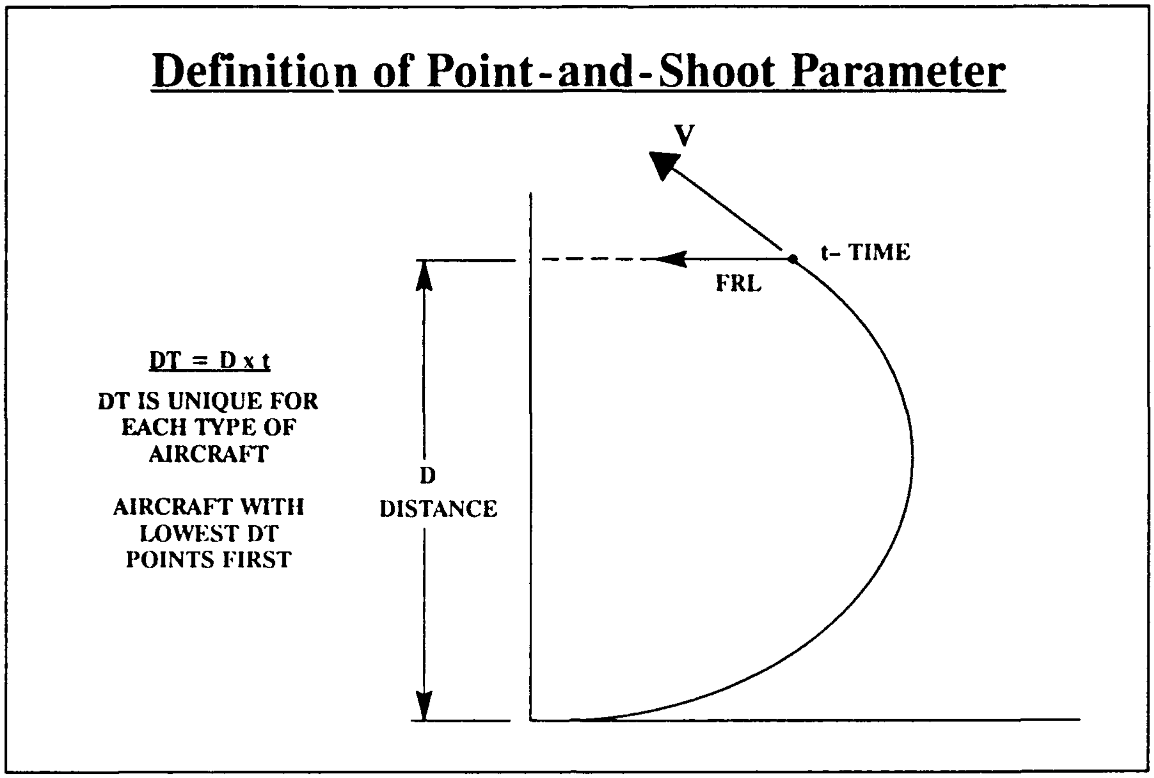


Figure 3. Definition of the Point and Shoot Parameter (10:17)

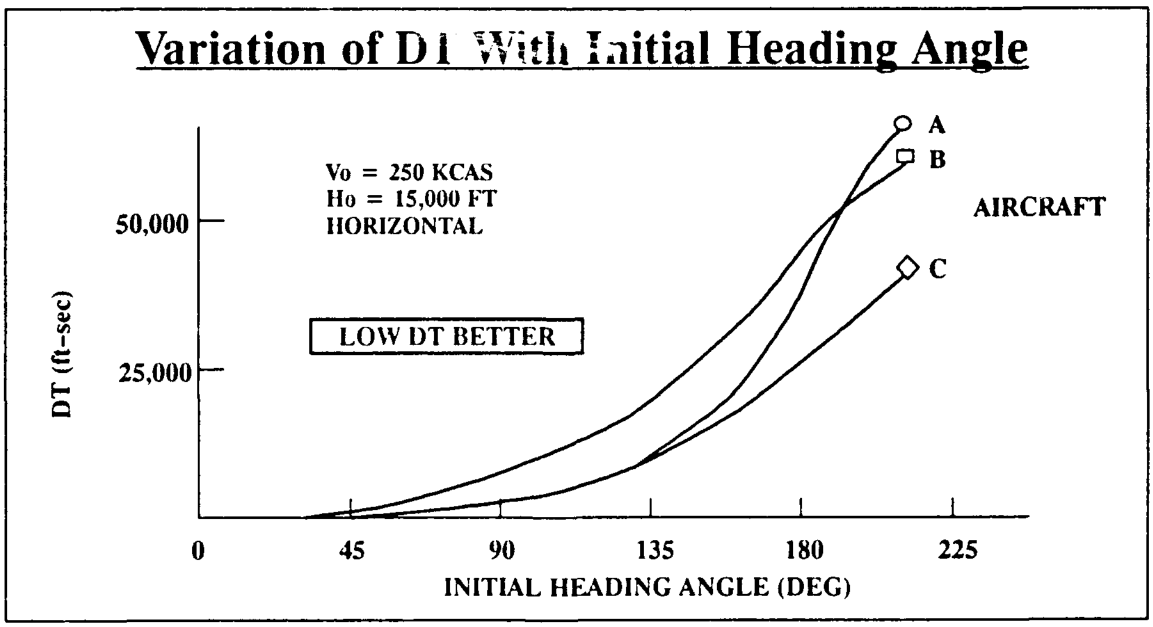


Figure 4. Suggested Format for the Point and Shoot Parameter (10:18)

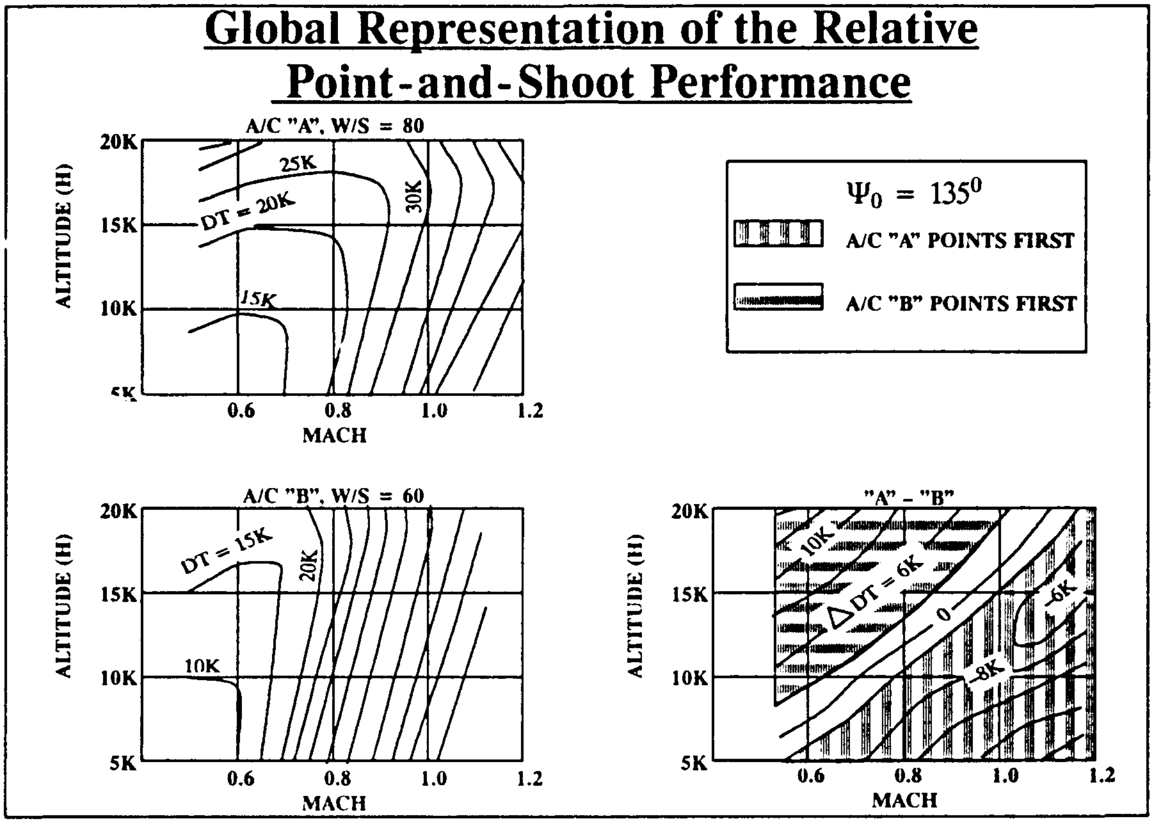


Figure 5. Suggested Format for the Global Dt Parameter (10:20)

The second metric which Kalviste and Tamrat present is the relative energy state metric which is defined as the ratio of the final maneuver velocity and the corner velocity. The maneuver has a two turn criteria which requires at least two 90 degree level turns before the velocity falls below the corner velocity. This definition and a suggested format for displaying the results are shown in Figure 6. This metric shows the relative energy state of an aircraft throughout a 180 degree level turn with respect to its maximum turn performance velocity.

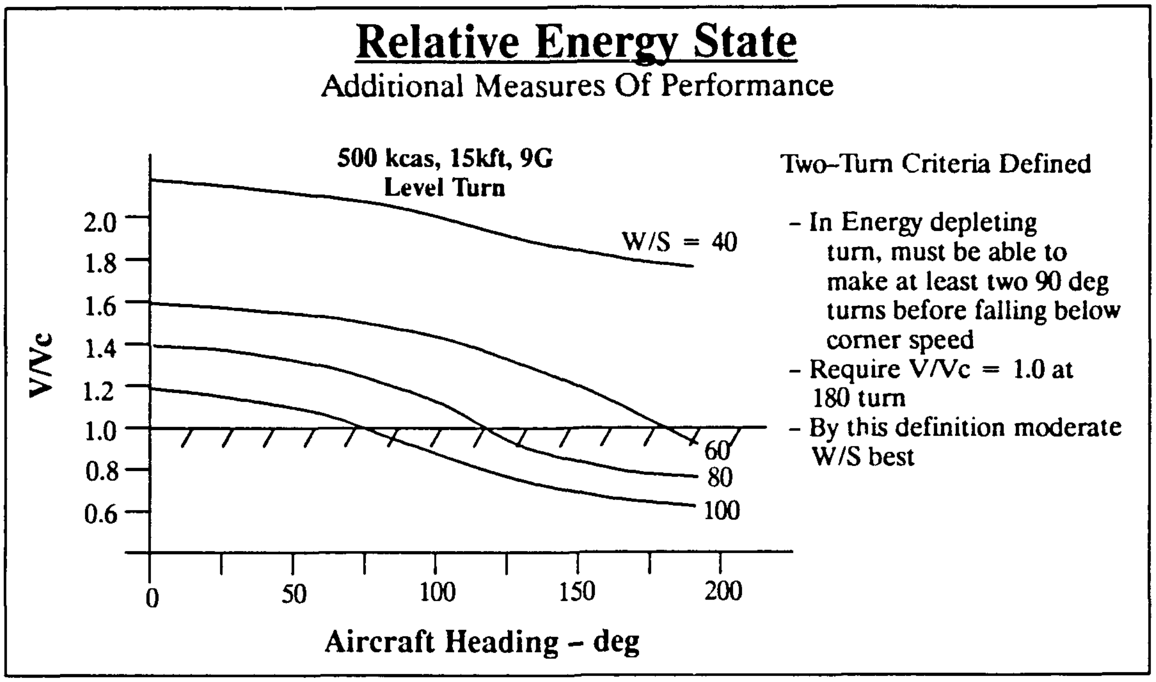


Figure 6. Suggested Format for the Relative Energy State Parameter (10:21)

The final metric by Kalviste and Tamrat is the combat cycle time. This metric is defined as the time required to make a prescribed heading change, unload and accelerate to its original velocity. Figure 7 provides a good description of this metric. A suggested format for presentation of this metric is given in Figure 8 which illustrates its value in aircraft design and comparison type studies. This metric gives some limited insight to an aircraft's ability to engage a target, unload and regain its original flying state.

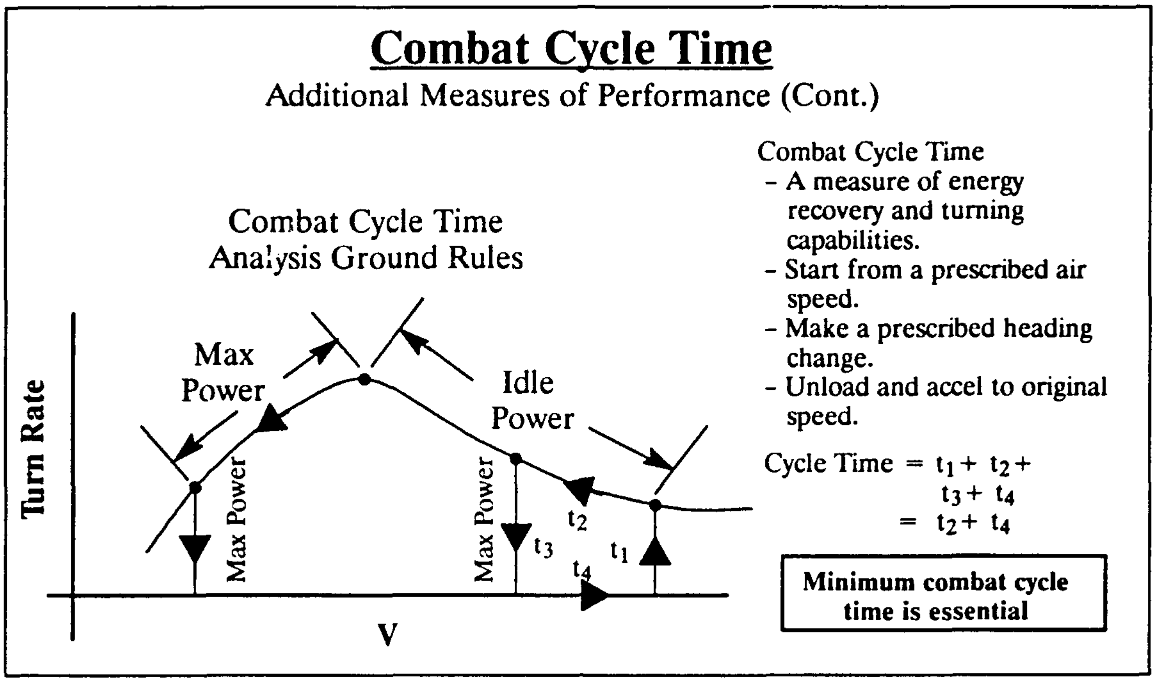


Figure 7. Description/Definition for the Combat Cycle Time (10:22)

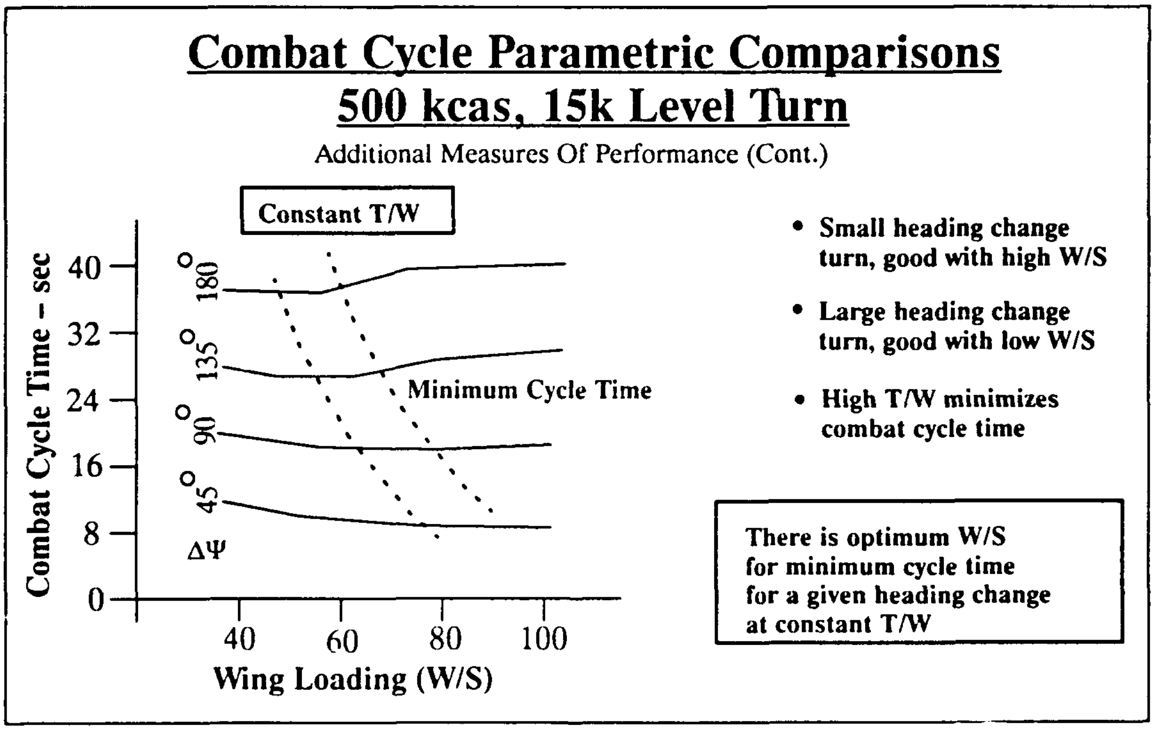


Figure 8. Suggested Format for the Combat Cycle Time (10:23)

The energy-agility metric, as proposed by Dorn (5), is defined in Equation 5 and is illustrated in Figure 9. This metric also shows an aircraft's efficiency at executing a prescribed maneuver and its ability to disengage and recover its original energy state.

$$EA = \int_{t_0}^{t_{k/r}} \Delta h_e \, dt \tag{5}$$

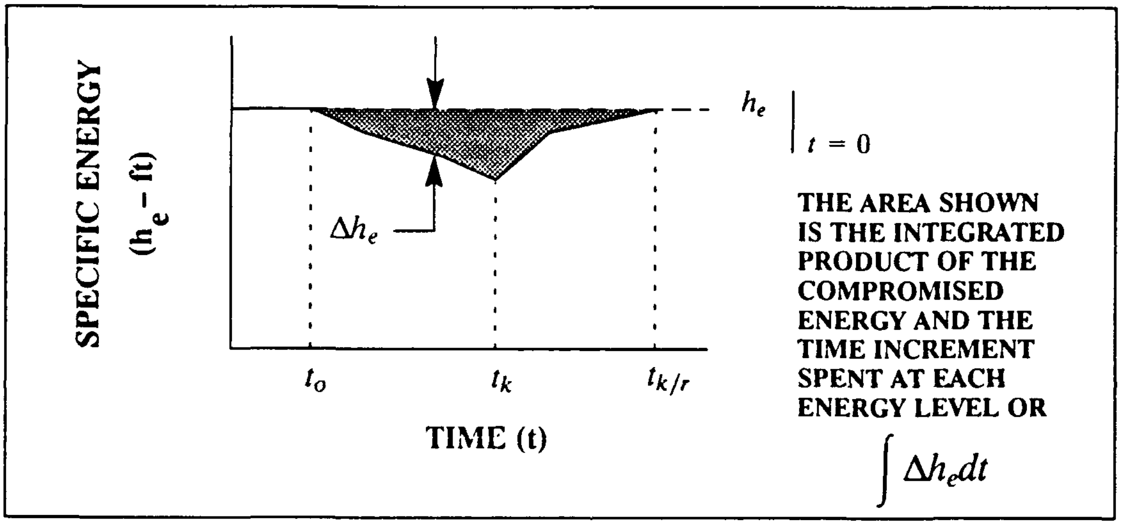


Figure 9. Definition of Energy-Agility (5:3)

Dorn suggests that this metric be used in conjunction with the other trajectory metrics in order to show the energy consumption during the maneuver. The form of this combination is shown in Equation 6 and is referred to as the "large-amplitude task agility" (5:5).

$$A^*_{l.a.t.} = \frac{(\frac{1}{DT})}{\int \Delta h_e dt} \tag{6}$$

It is interesting to note that Dorn's Large Amplitude Task agility metric includes the merits of all three of Kalviste/Tamrat's metrics. It not only shows an aircraft's ability to turn but also accounts for the aircraft's efficiency at making the turn. To date, this metric has only been proposed and no known work in quantification has been published.

The last metric which will be discussed is the dynamic speed turn plots as proposed by McAtee (11:11–15). These plots, as shown in Figure 10, are generated from a crossplot of information contained in the classic turn rate versus airspeed plot which is typically called a 'doghouse plot'.

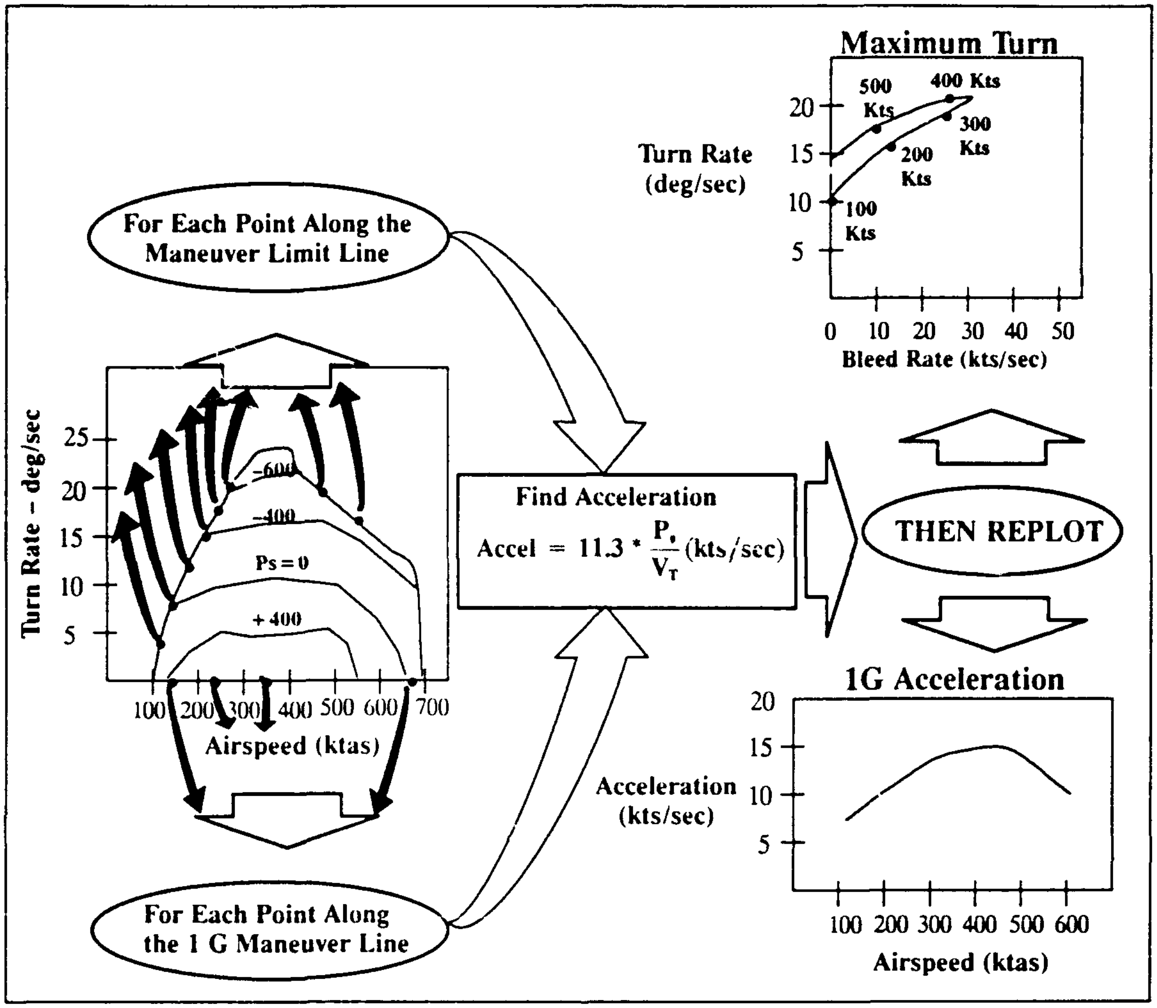


Figure 10. Definition of Dynamic Speed Turn Plots (11:12)

These plots show the efficiency of an aircraft performing a maximum performance turn and a 1 G acceleration. Quantification work on this metric has been identified in Figure 1 as on going, but no known results have been published to date.

The metrics which have been presented in this summary were used in the following research effort. The approach taken in this effort, as described in the following section, was intended to introduce the current metrics and expand on

their intent and format in order to determine their applicability in evaluating combat effectiveness.

General Approach

The three objectives of this research were; 1) implementation of the *agility* metrics into a single analysis tool; 2) correlation of some aircraft design metrics to the *agility* metrics and 3) determination of the sensitivities between an aircraft's trajectory performance and the *agility* and design metrics. The approach taken to accomplish these objectives was as follows; 1) computer based algorithms were developed for the quantification of the various *agility* metrics; 2) a parametric study between the *agility* and design metrics was performed to determine their correlation and 3) various aircraft states and characteristics were used to quantify the agility metrics and were also used as inputs to the trajectory simulations of some simple air-combat maneuvers. The results of these calculations and simulations were then tabulated and used in a comparative analysis.

Sequence of Presentation

Following this introductory material, Chapter 2 presents the details of the algorithm development, the parametric analysis of the *agility* metrics and the correlation method used in the comparative analysis. The results of this research effort are then presented in Chapter 3 with discussion of the problems, limitations and validity of the analyses. Chapter 4 then finalizes the study by providing the conclusions and recommendations which have resulted from this effort.

II. Methodology

This chapter presents the details into the investigation of the advanced aircraft performance measures of merit. These details describe the overall approach taken in this study which is shown in Figure 11. The individual blocks are examined and supporting arguments are provided for the individual performance metrics.

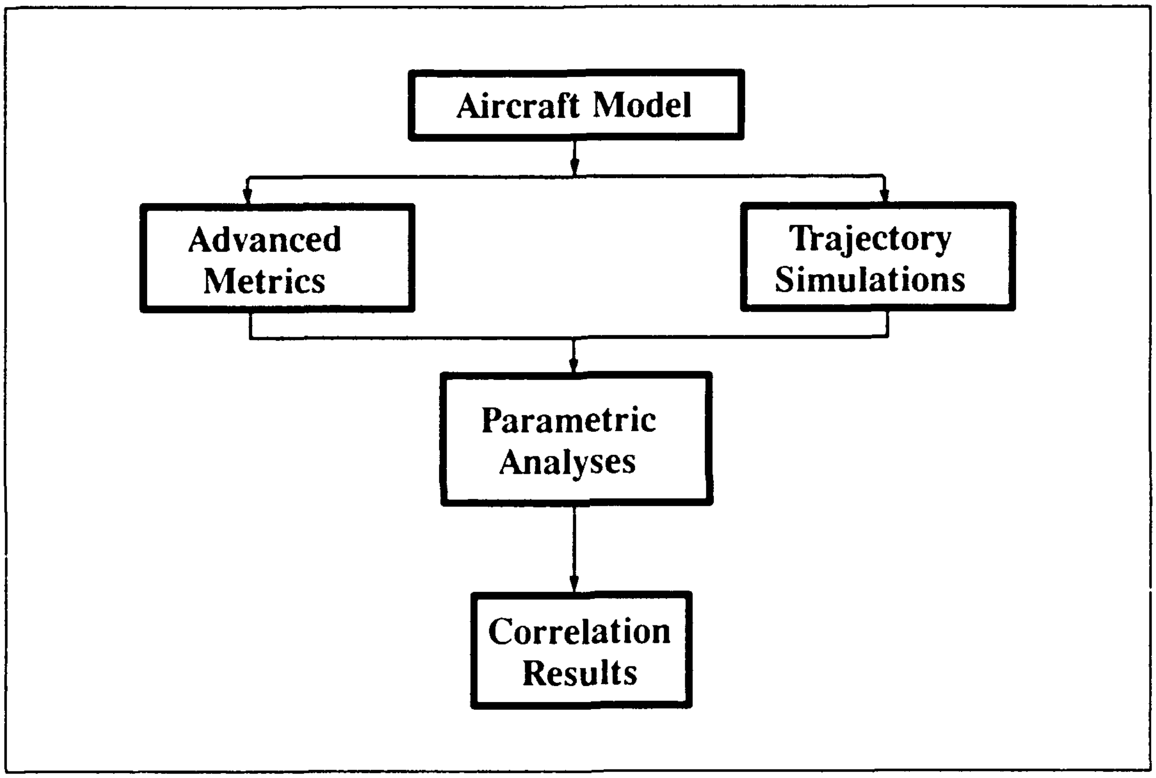


Figure 11. Methodology Framework

Aircraft Model

An aircraft model (F-99A) was developed for this study to be used in the quantification and analysis of the advanced performance metrics and the trajectory simulations. This model is intended to be characteristic of current light weight fighter (LWF) designs. These characteristics are modeled simplistically in order to facilitate manual validation of the results and to provide a better understanding of

the resulting performance trends. The model is based on the following types of data; 1) configuration; 2) point mass and 3) inertial.

The configuration data, shown in Table 1, represents a typical LWF design in weight, size and limitations. The values for thrust to weight ratio (T/W) and wing loading (W/S) are used later in this study in a parametric analysis of the various performance metrics.

Table 1

Configuration Data

Wing Area	=	**300 FT^2**
Weight	=	**20000 LBS**
T/W Ratio	=	**1.66 @ sea level**
W/S Ratio	=	**66.7 LBS/FT^2**
Mach Limit	=	**2.5**
No of Engines	=	**1**

The point mass data includes the trimmed aerodynamic data and the installed propulsion data. This data is presented in Figures 12 thru 18. The aerodynamic data is typical of a conventional wing planform aircraft and has been simplified by using a linear relationship between the lift coefficient (C_L) and the angle of attack (α) and a parabolic relationship between C_L and the drag coefficient (C_D). The relationship of C_{D_0} ($C_L = 0$) versus Mach has been modeled, as well as C_D due to speed brake deployment and $C_{L_{max}}$ versus Mach. The lift and drag relationships are then represented by the following classic equations.

$$L = \frac{1}{2}\varrho V^2 S C_L \tag{7}$$

$$D = \frac{1}{2}\varrho V^2 S C_D \tag{8}$$

where $$C_D = (C_{D_0} + C_{D_L} + C_{D_{SB}})$$

ϱ is the air density

V is the true airspeed

S is the wing area

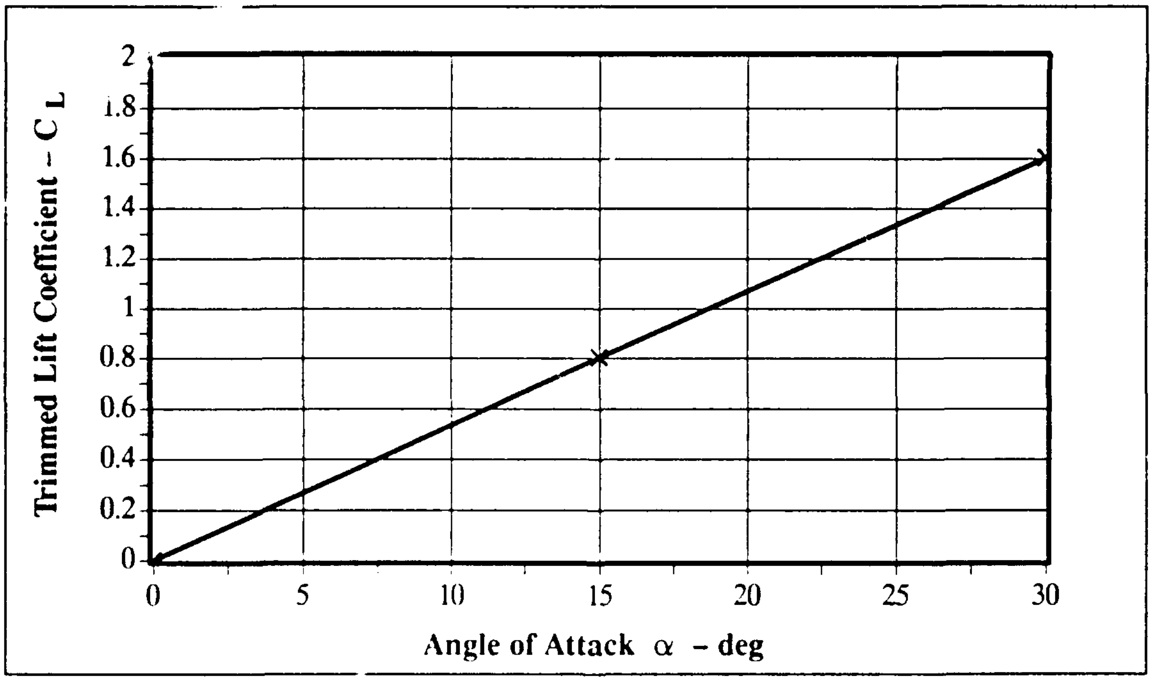


Figure 12. F-99A Trimmed C_L vs α

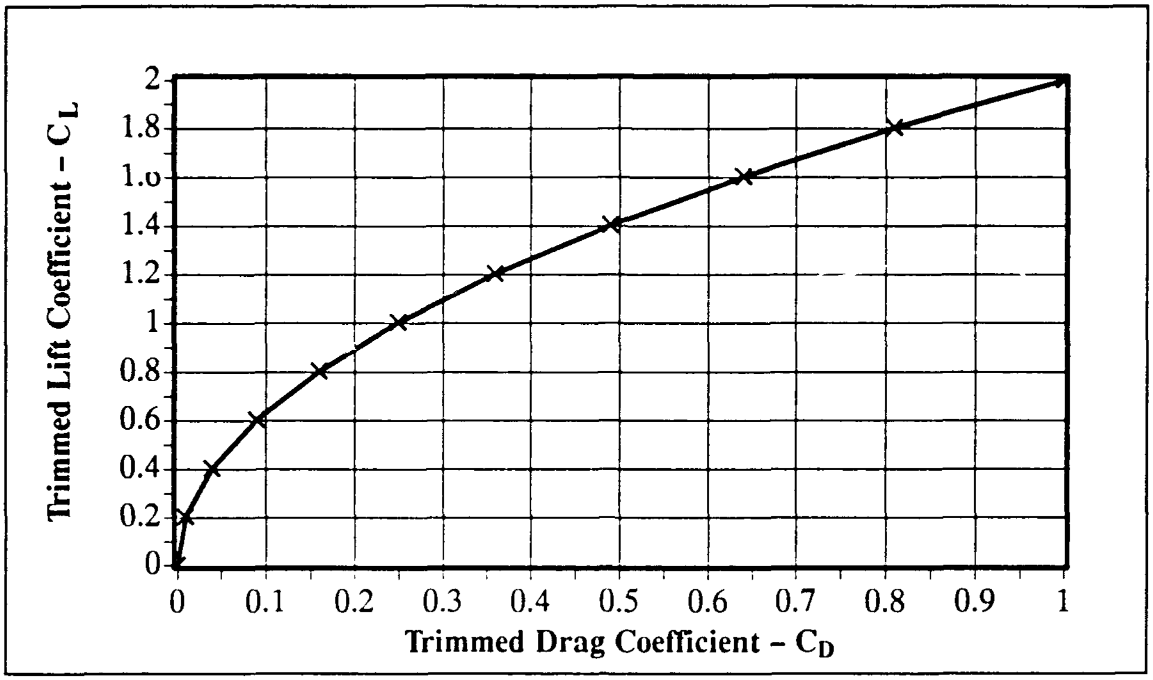


Figure 13. F-99A Trimmed Drag due to Lift (C_L vs C_D)

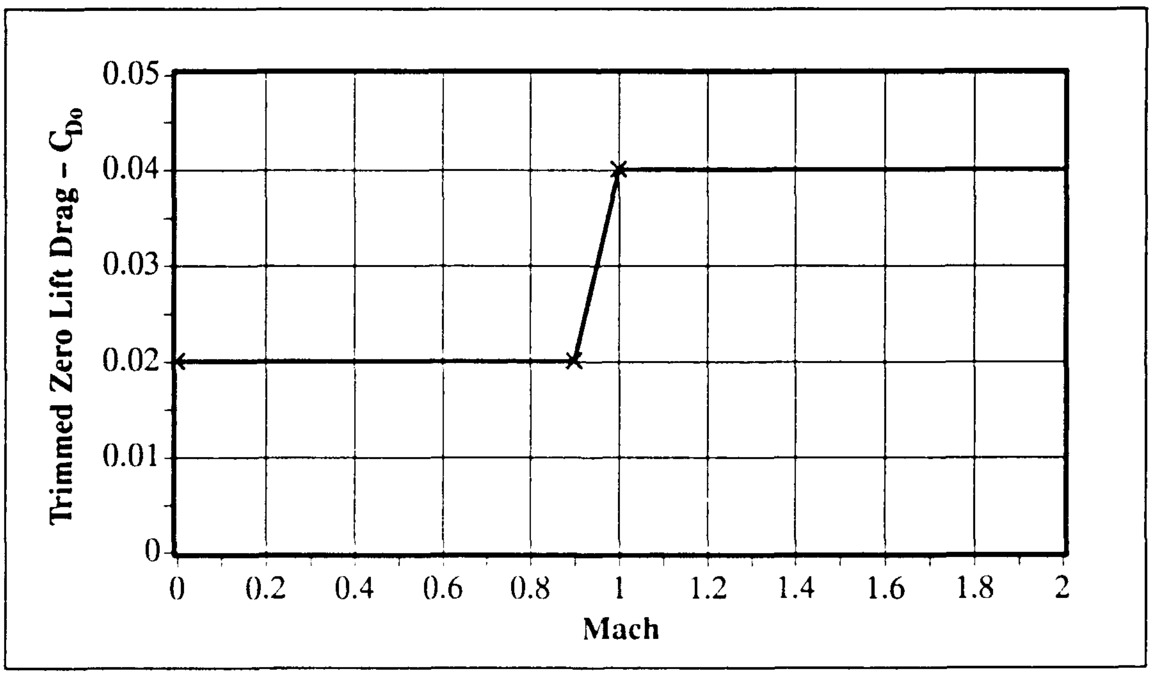


Figure 14. F-99A Trimmed Zero Lift Drag (C_{D_0}) vs Mach

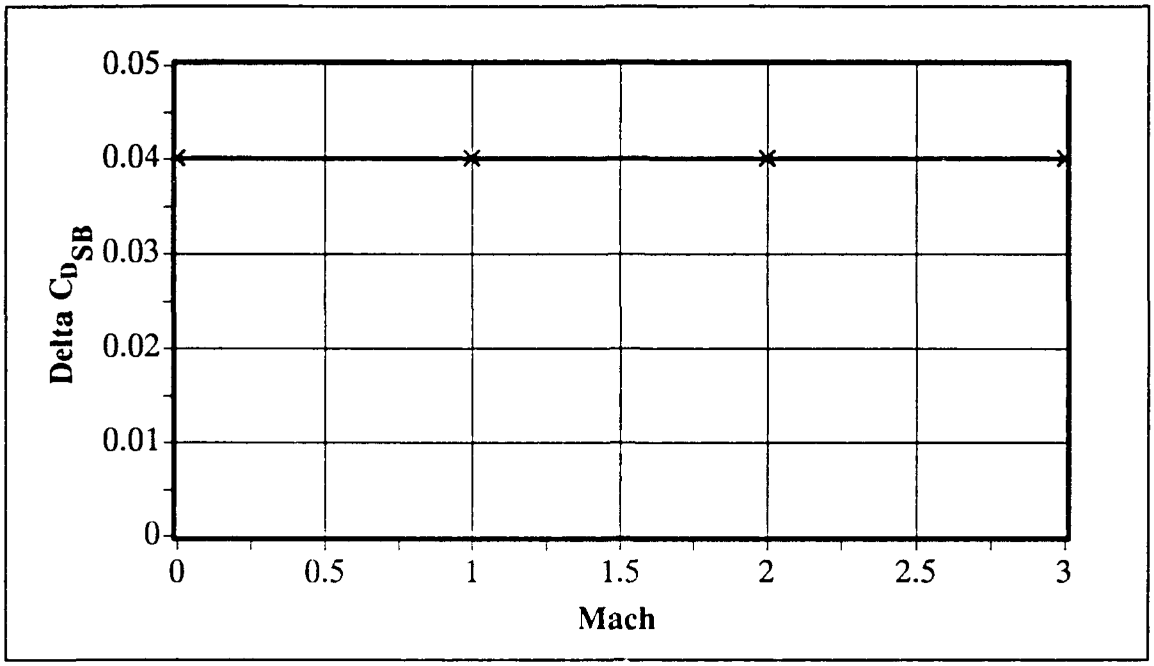


Figure 15. Speed Brake Drag vs Mach

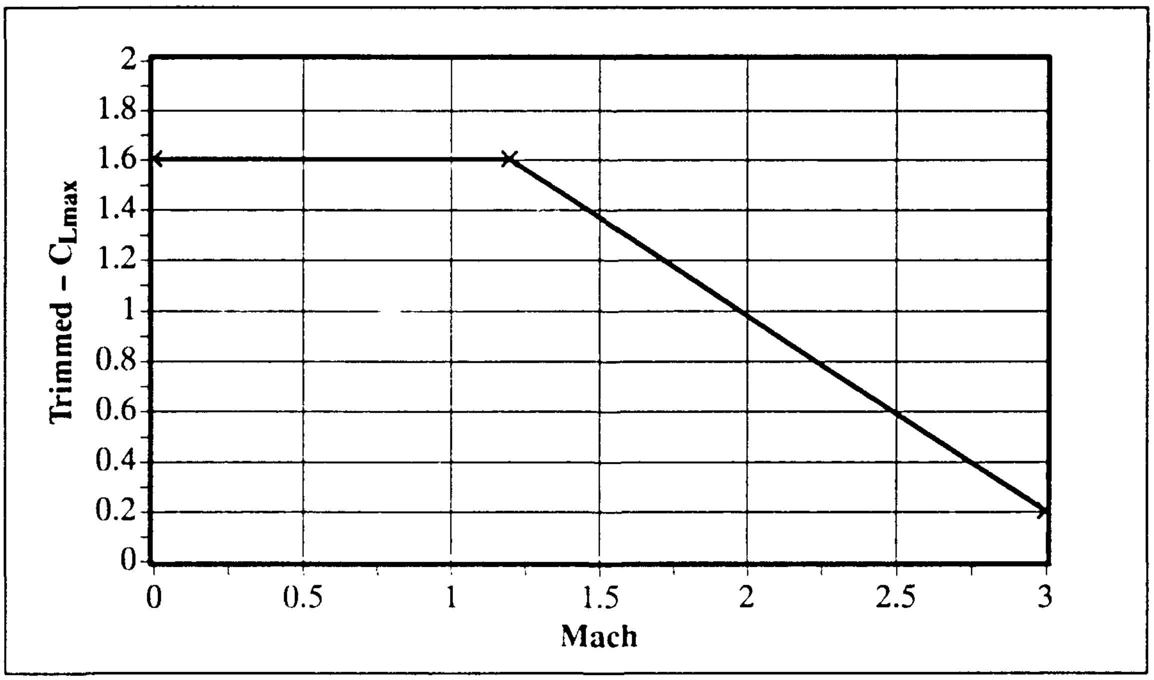


Figure 16. F-99A Trimmed C_{Lmax} vs Mach

The propulsion data has been modeled with characteristic trends in altitude and Mach for the following power settings; 1) maximum afterburner; 2) military rated and 3) idle thrust.

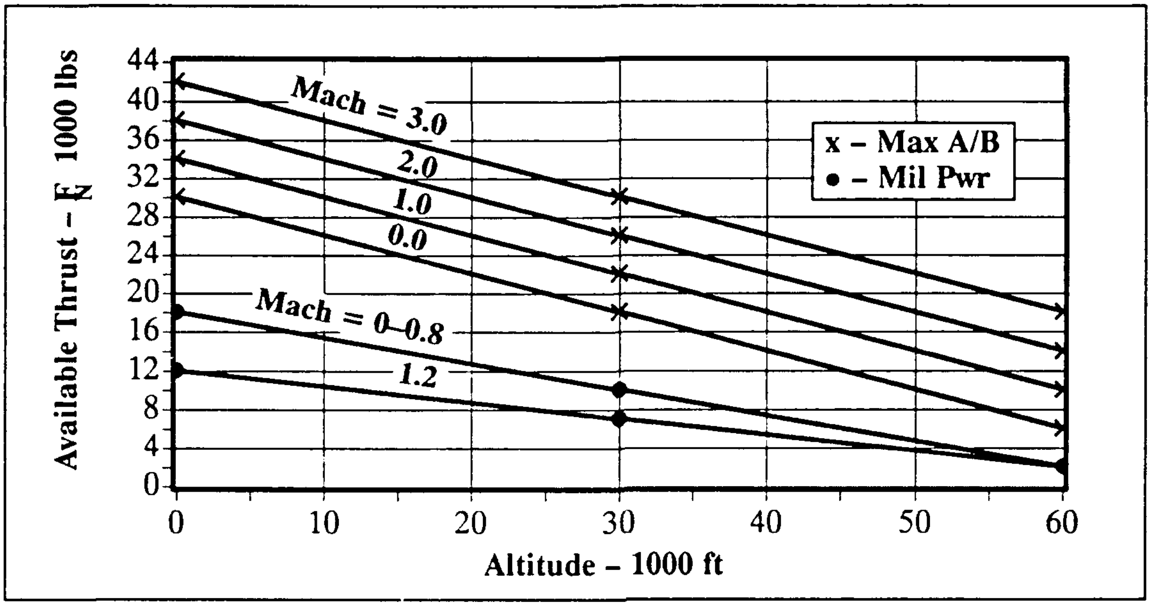


Figure 17. Available Thrust vs Altitude

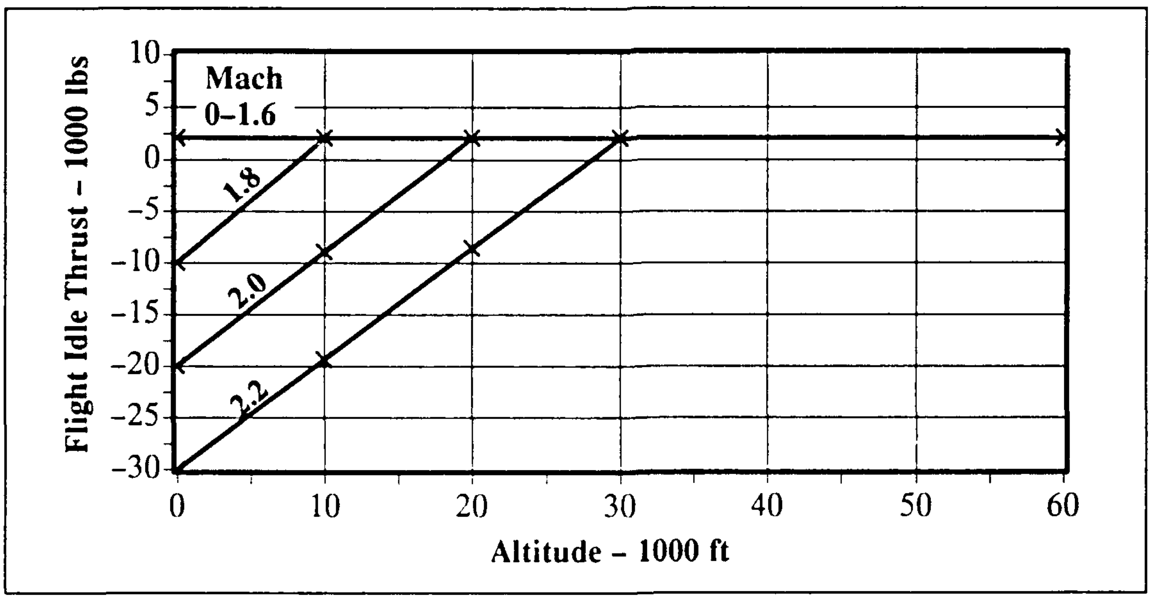


Figure 18. Flight Idle Thrust vs Altitude

The inertial data, presented in Figures 19 thru 21, show the times required for the aircraft to; 1) roll and capture 90 degrees of bank angle; 2) pitch and capture a desired pitch attitude and 3) spool down an engine from maximum power revolutions per minute (RPM) to idle power RPM. This data has been modeled to show typical design trends with load factor and speed and is used later in the parametric analysis of the performance metrics.

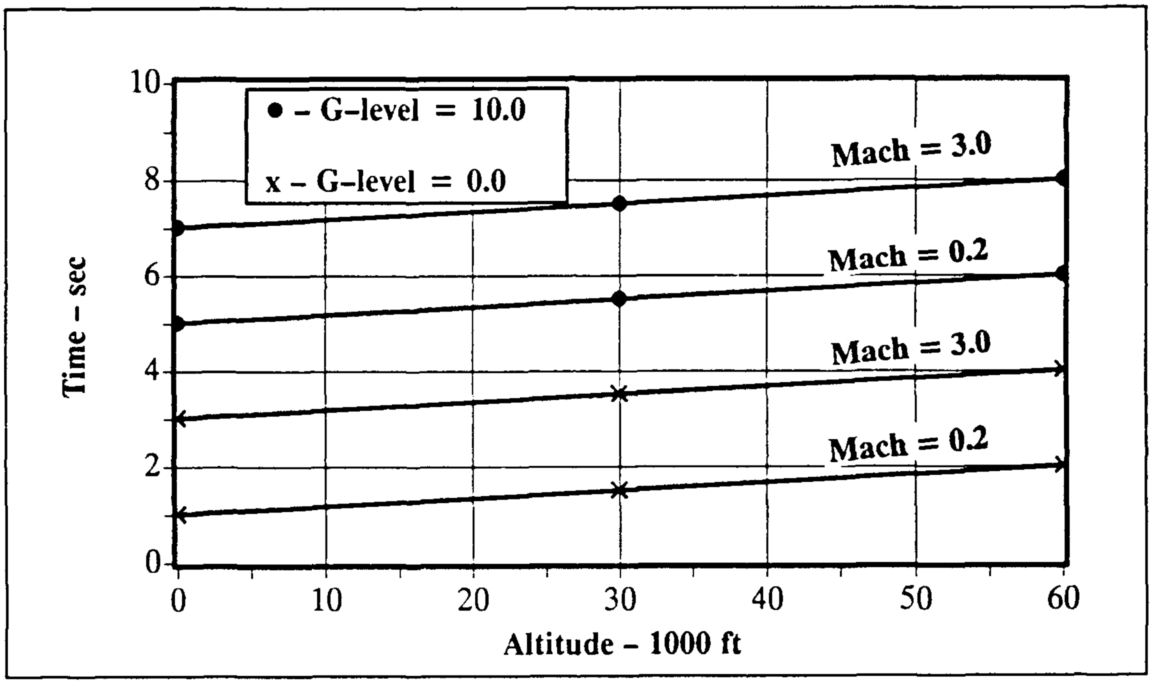


Figure 19. Time to Capture 90 Deg Bank Angle Change

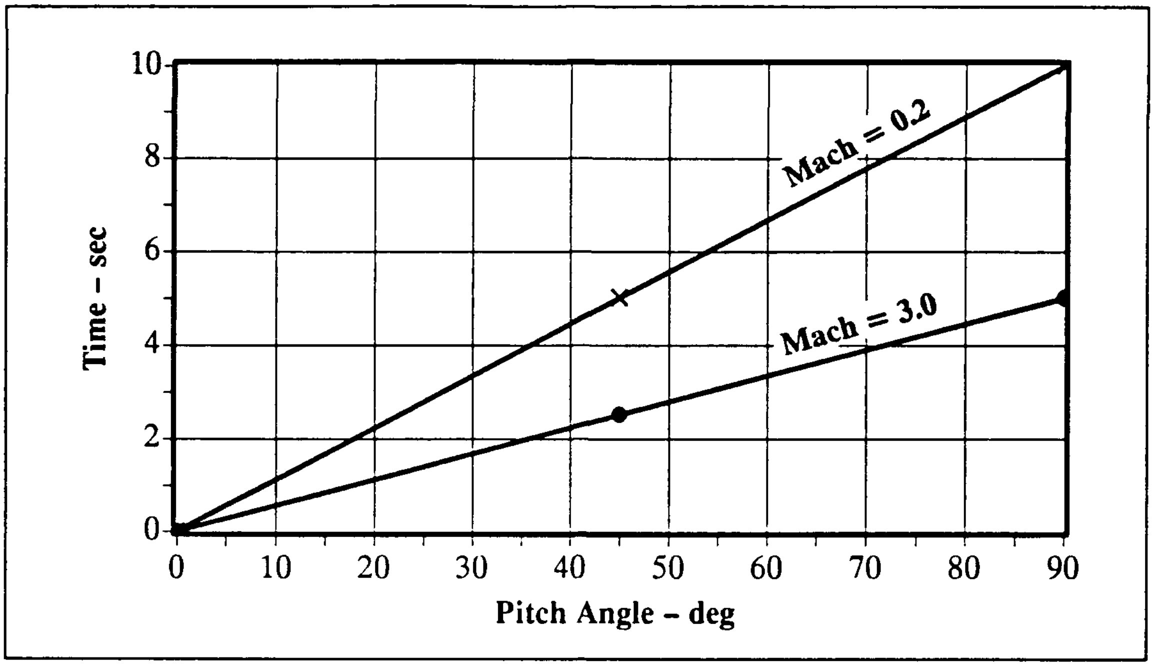


Figure 20. Time to Pitch and Capture Desired Pitch Attitude

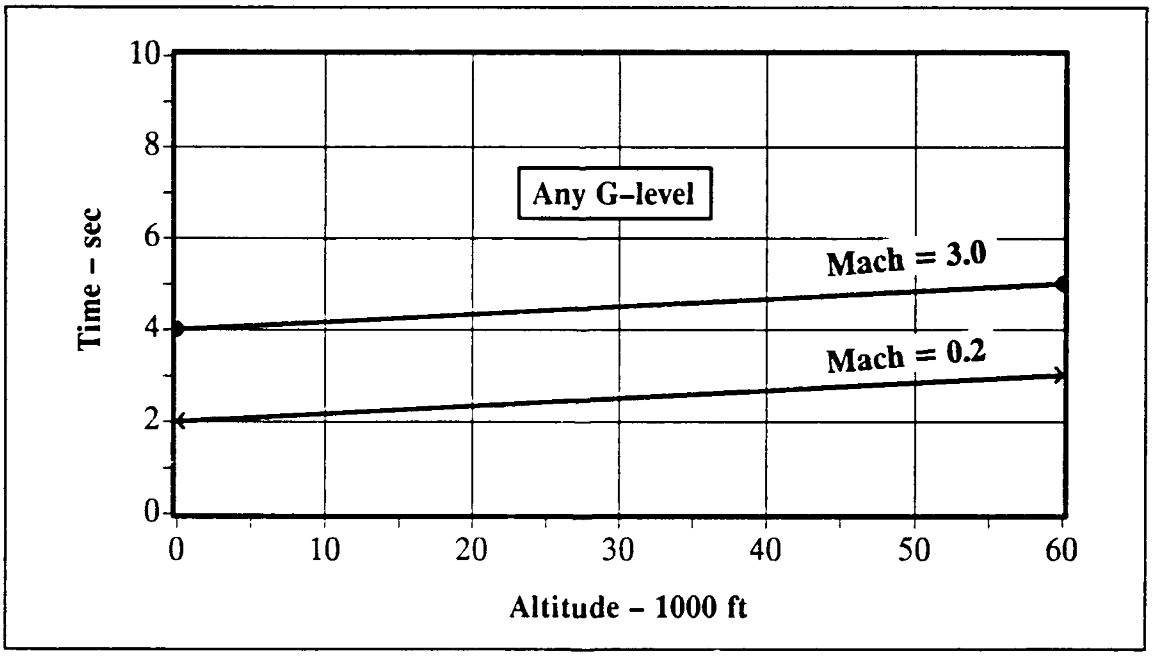


Figure 21. Time to Change P_s States

Advanced Metrics Development

The approach taken to develop the individual metrics was to; 1) restate the specific performance metric and the supporting arguments and 2) develop the algorithms for quantification of the metric. The attempt in this approach was to expand on the intent of the metric by showing the results with various independent variables.

Herbst's Metrics

As previously shown in Chapter 1, Herbst proposes that an aircraft's agility can be analytically derived by taking the second inertial time derivative of the velocity vector. The derivative was shown in Equation 1 and is fully derived in Appendix A. The resulting component terms give rise to force onset relations called longitudinal and curvature agility and to a torque onset relation (maneuver plane rotation onset) called torsional agility. Figure 22 illustrates the maneuvers which Herbst proposes for quantification of his agility metrics.

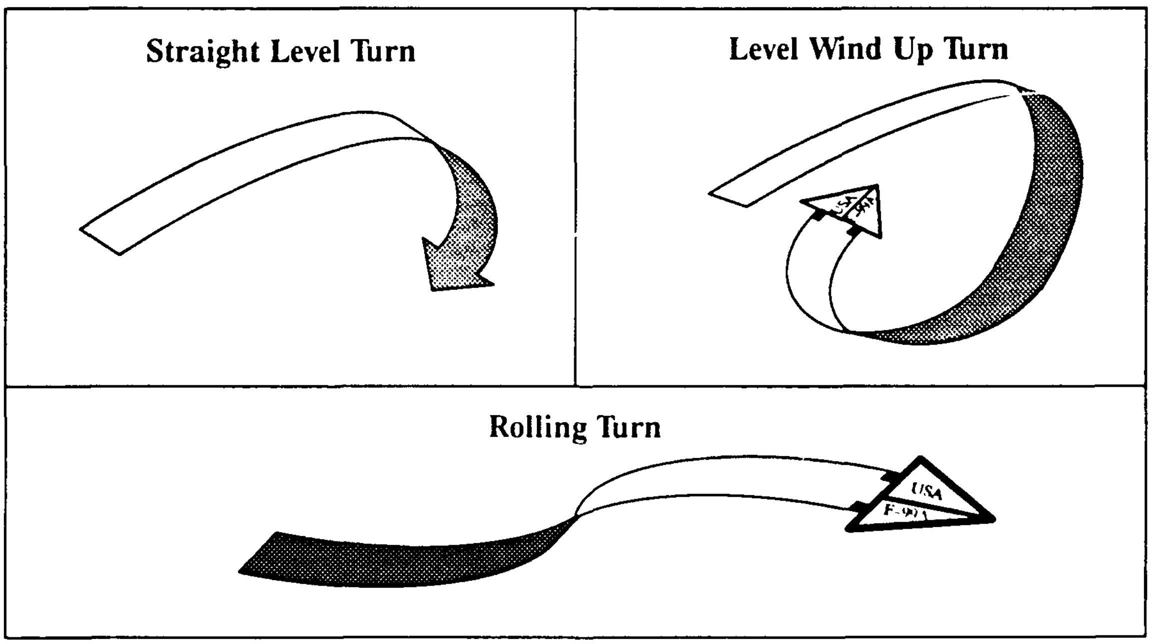


Figure 22. Herbst's Agility Quantification Maneuvers

A different approach was taken for this study, which also took the second inertial time derivative of the velocity vector. Actually, the starting point was to take the first inertial time derivative of Newton's 2nd Law of Motion as shown in Equations 9 and 10.

$$\vec{F} = m\vec{A} \tag{9}$$

$$\frac{{}^{I}d\vec{F}}{dt} = \frac{{}^{I}dm\vec{A}}{dt} \tag{10}$$

For a complete derivation of this equation see Appendix A. The results of this derivation are shown in Equations 11 thru 13.

Axial Agility

$$\begin{aligned}\ddot{V} = (\frac{g}{W_T})[(\dot{T}\cos a - T\dot{a}\sin a - \dot{D}) - \dot{W}_T(\sin\gamma + \frac{\dot{V}}{g}) \\ -(T\sin a + L)(\dot{\gamma}\cos\phi + \dot{\psi}\cos\gamma\sin\phi)] \\ + V[(\dot{\gamma}\cos\phi + \dot{\psi}\cos\gamma\sin\phi)^2 + (\dot{\psi}\cos\gamma\cos\phi - \dot{\gamma}\sin\phi)^2]\end{aligned} \tag{11}$$

Turn Agility

$$\begin{aligned}\ddot{\psi} = (\frac{1}{V\cos\gamma})[(\frac{g}{W_T})[(T\sin a + L)(\dot{\phi} - \dot{\psi}\sin\gamma)\cos\phi \\ + (T\cos a - D)(\dot{\psi}\cos\gamma) + (\dot{L} + \dot{T}\sin a + T\dot{a}\cos a)\sin\phi \\ - \dot{W}_T(\frac{V}{g})\dot{\psi}\cos\gamma] - 2\dot{V}\dot{\psi}\cos\gamma + 2V\dot{\psi}\dot{\gamma}\sin\gamma]\end{aligned} \tag{12}$$

Pitch Agility

$$
\begin{aligned}
\ddot{\gamma} = (\frac{1}{V})[(\frac{-g}{W_T})[&(T\sin\alpha + L)(\dot{\phi} - \dot{\psi}\sin\gamma)\sin\phi - (T\cos\alpha - D)\dot{\gamma} \\
&-(\dot{L} + \dot{T}\sin\alpha + T\dot{\alpha}\cos\alpha)\cos\phi + \dot{W}_T(\frac{V\dot{\gamma}}{g} + \cos\gamma)] \\
&-2\dot{V}\dot{\gamma} - V\dot{\psi}^2\sin\gamma\cos\gamma]
\end{aligned} \qquad \textbf{(13)}
$$

An algorithm was then developed which incorporates these equations into procedures for computations of the agility metrics versus Mach, at constant weight and altitude with contours of constant load factor. The reason for this choice of constraints was to possibly identify a Mach for optimum agility. This algorithm is shown by flow chart in Figure 23.

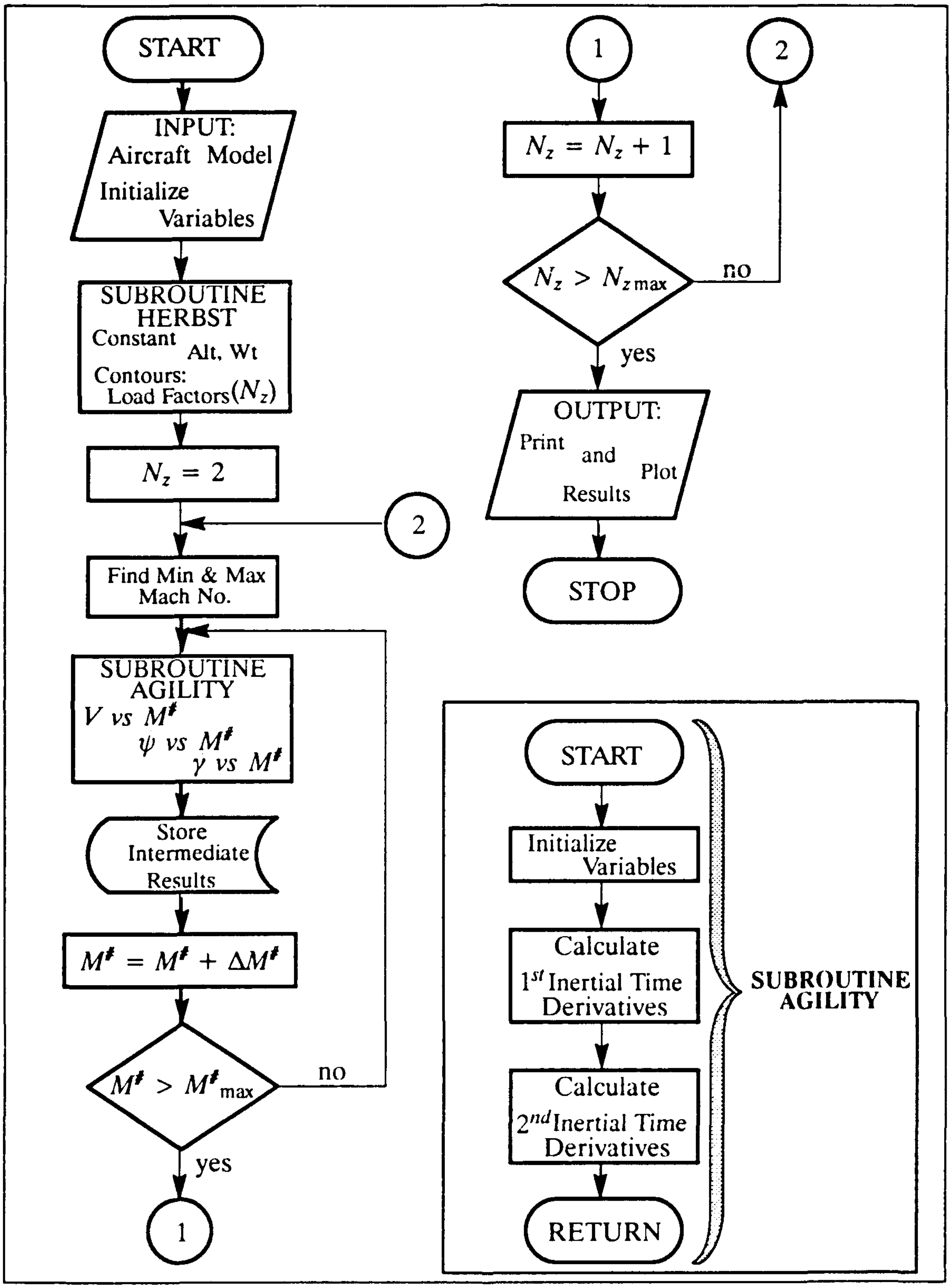


Figure 23. Algorithm for Quantifying Herbst's Metrics

Eidetics' Metrics

The Eidetics corporation (Skow, et. al.) was one of the first to devote a significant amount of effort into the development and quantification of the *agility* metrics (15, 16). The results of their time and effort gave the definitions of agility as described in Chapter 1, Equations 2 thru 4. These metrics combined classic performance measures of merit with characteristic times which are apparently related to the classic metrics. For instance, if you consider a rolling scissors maneuver, as shown in Figure 24, the combined effect of the time it takes to reverse the turn and the instantaneous turn rate capability of the aircraft contribute to give a performance advantage. Thus, the combination of terms which define Torsional Agility (TA), Equation 2, appear to be able to predict combat effectiveness.

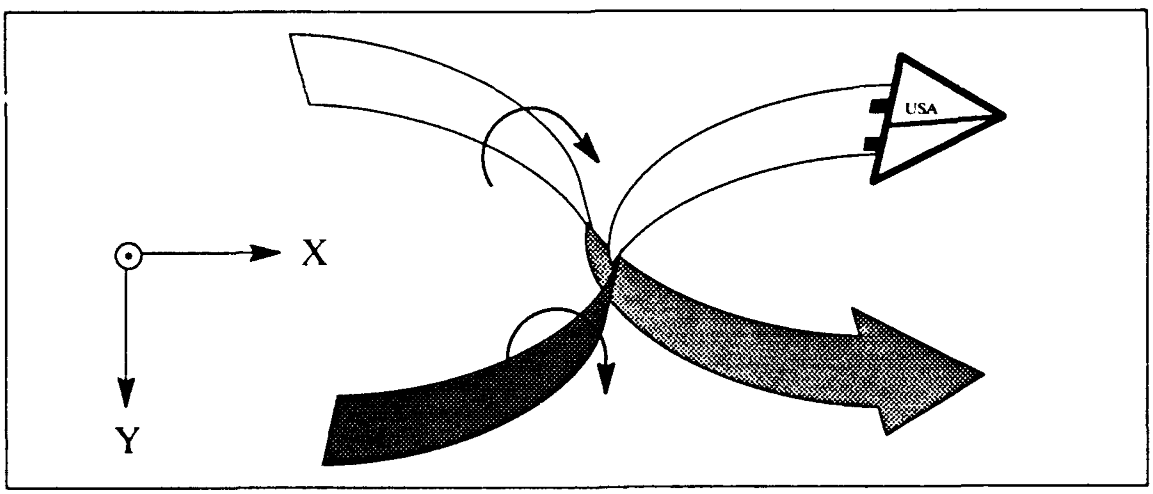


Figure 24. Rolling Scissors Maneuver

Axial Agility (AA) as defined by Eidetics, Equation 3, attempts to quantify the aircraft's maximum acceleration/deceleration capability. This information might be useful to the pilot of an aircraft who is trying to achieve and maintain the maximum turn capability (corner velocity V_C) from a high speed condition.

Pitch Agility, as defined in Equation 4, is the time required to achieve and maintain a desired pitch attitude. This metric relates directly to controllability in the pitch plane of the aircraft. The significance of this metric is apparent in situations where tight attitude control may be necessary for targeting solution or where recovery from a slow speed, high pitch condition is necessary for a safe disengagement.

The approach taken to quantify Eidetics' metrics was to develop a series of algorithms which would yield multiple crossplots of the resulting agility computations. The intent of this approach was to determine if any optimal solutions existed which could provide guidance into the execution of certain maneuvers. Figures 25 and 26 illustrate the basic algorithms used in the quantification of TA and AA. For this study, PA was part of the assumed aircraft model and its quantification was not pursued further.

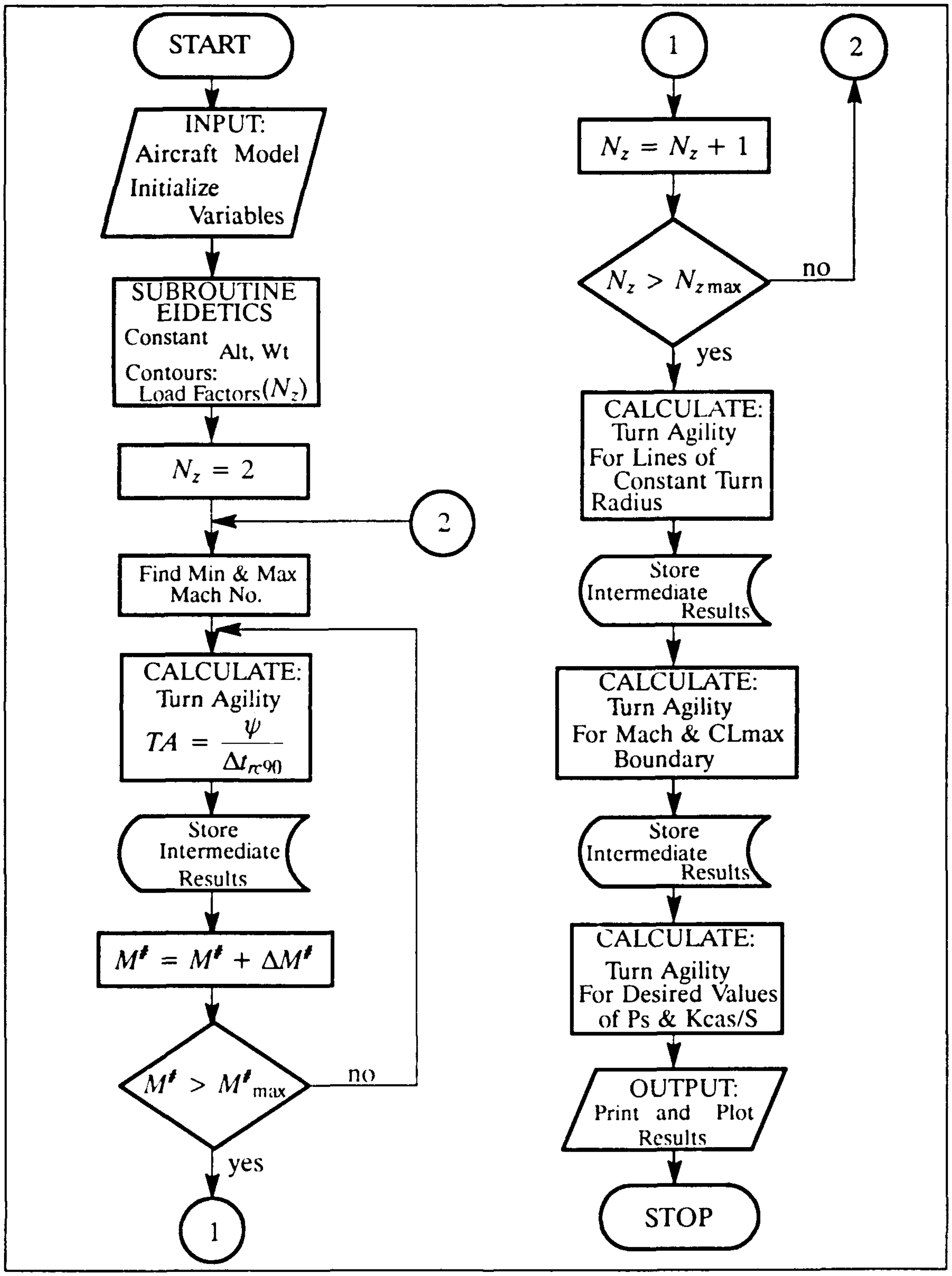


Figure 25. Algorithm for Eidetics' Torsional Agility (TA vs $M^\#$, N_Z contours)

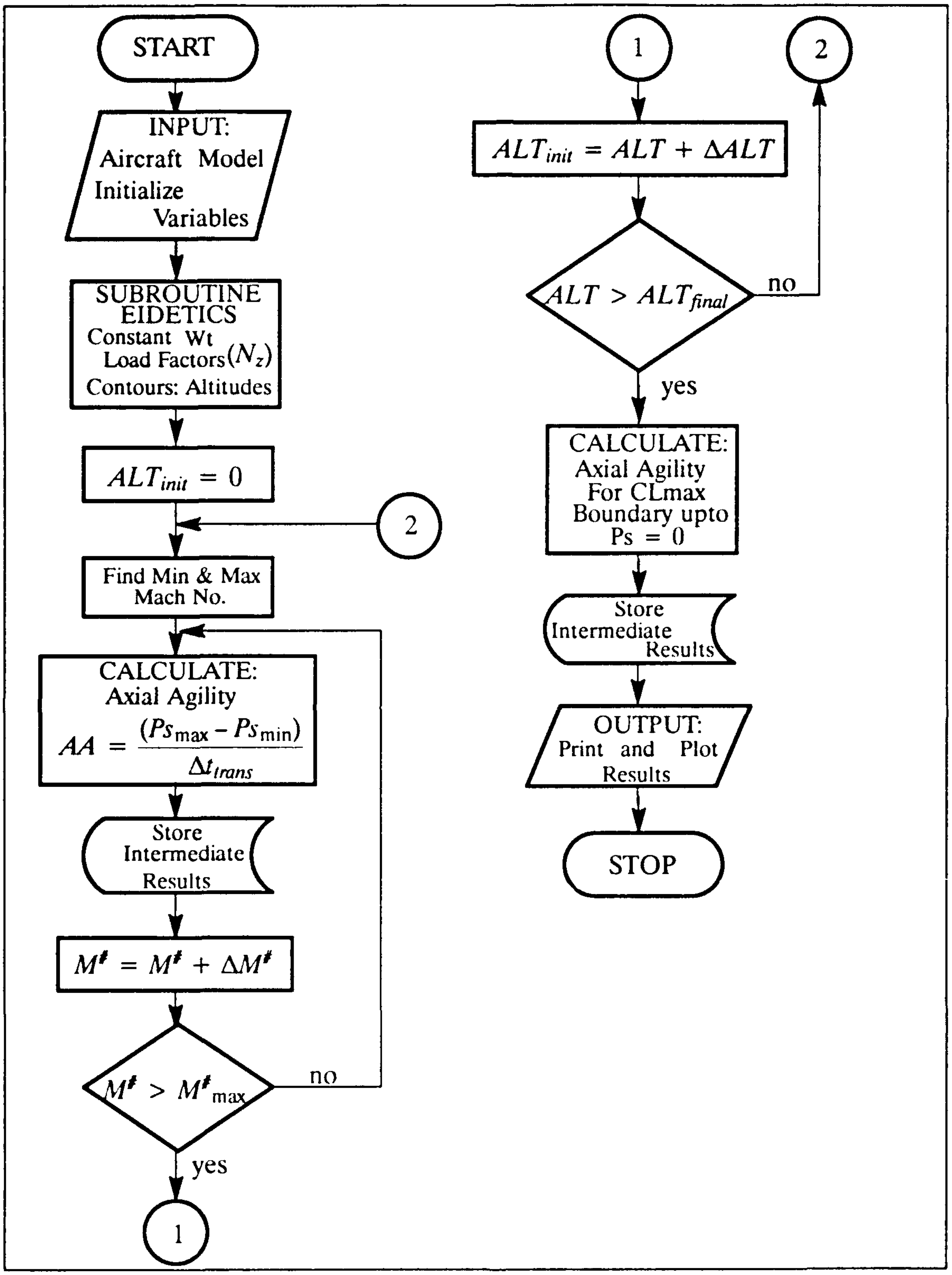


Figure 26. Algorithm for Eidetics' Axial Agility (AA vs M#, Alt contours)

Kalviste's Metrics

The metrics proposed by Kalviste and Tamrat (DT, V/V_C, CCT), result from either computer simulation or flight test of a simple flight maneuver as explained in Chapter 1. These metrics were designed to quantify the pointing ability and energy level during a one-circle engagement and to assess the aircraft's ability to complete the engagement and then disengage to recover its original energy state. In particular, the DT metric attempts to approximate a dual aircraft, one circle engagement by a solo aircraft maneuver. This 'open-loop' parameter is used to measure the aircraft's 'closed-loop' pointing capability which gives designers and evaluators the ability to quantify the fighting capability of a single aircraft without considering a second advisory aircraft.

In this study, these metrics were quantified by utilizing a trajectory simulation program which was modified to specifically calculate the DT metric and to record the V/V_C and CCT values for a matrix of initial Mach and altitude conditions. The algorithm developed for this purpose is shown in Figure 27. The results from running the Mach and altitude matrix were then crossplotted to obtain various viewpoints of the performance trends.

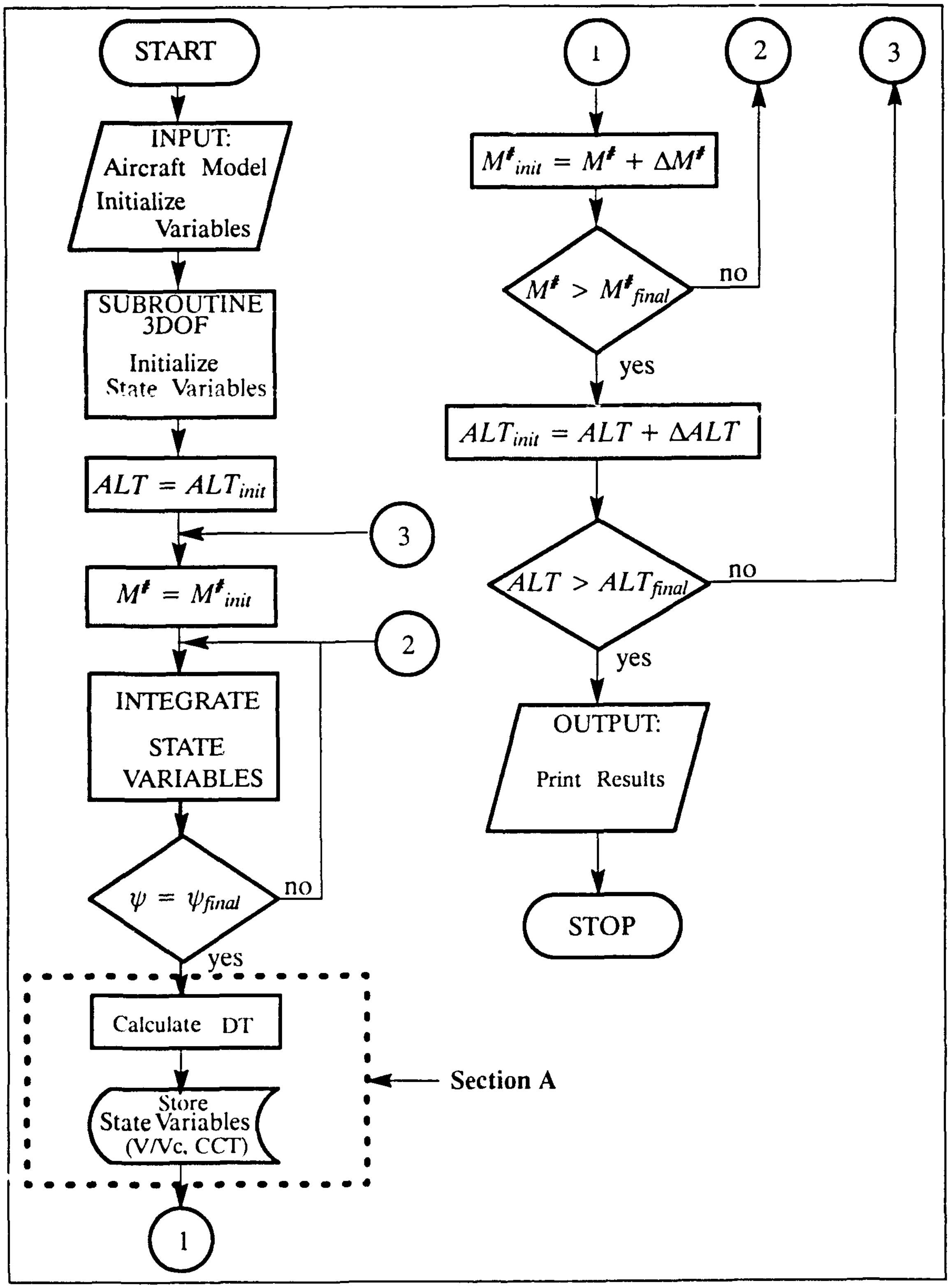


Figure 27. Algorithm for Quantifying Kalviste's Metrics

Dorn's Metrics

The Energy Agility (EA) and Large Amplitude Task Agility ($A_{L.A.T.}$) metrics which Dorn proposes are directly related to the metrics proposed by Kalviste and Tamrat. The supporting arguments for these metrics are also the same as stated above. The only difference between the two approaches is that Dorn combines the merits of Kalviste and Tamrat's metrics into a single parameter. This combination allows for the quantification of the aircraft's pointing capability while tempering this result with the energy consumed during the maneuver. The approach taken to quantify this metric was the same as described for Kalviste except that the EA calculation was included and the calculation of DT was replaced by the $A_{L.A.T.}$ relation. This approach is illustrated in Figure 28 which shows the modification to Section A of Kalviste and Tamrat's algorithm, Figure 27.

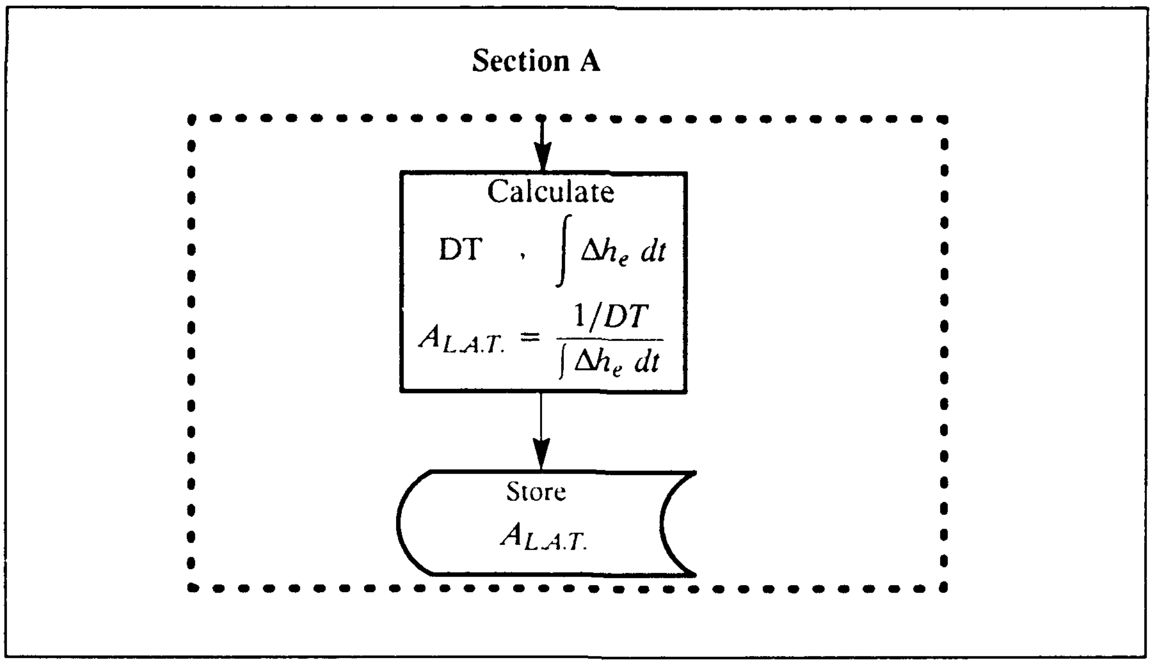


Figure 28. Algorithm Modification to Quantify Dorn's Metrics

McAtee's Metrics

The dynamic speed turn plots by McAtee as illustrated in Chapter 1, Figure 10, provide additional information about an aircraft's turn performance which is not readily available from the classic turn rate chart called the 'doghouse plot'. The DST plots are generated from the information contained in these charts and provide some insight into optimal maneuvering conditions.

The approach taken for this study was to provide the same information as the DST plots except that this information was plotted back onto the 'doghouse plot'. The reason for this change was to provide as much information as possible into one performance chart which best describes the aircraft's turning capability. This approach was developed by the author (et. al.) and is currently incorporated in the U.S. Air Force combat tactics manuals (MCM 3-1). Figure 29 shows the algorithm which was developed to include the acceleration/deceleration information along with the classic 'doghouse plot'. It is interesting to note that the suggestion to include this type of information into the 'doghouse plot' came from the operational users of the data, the pilots.

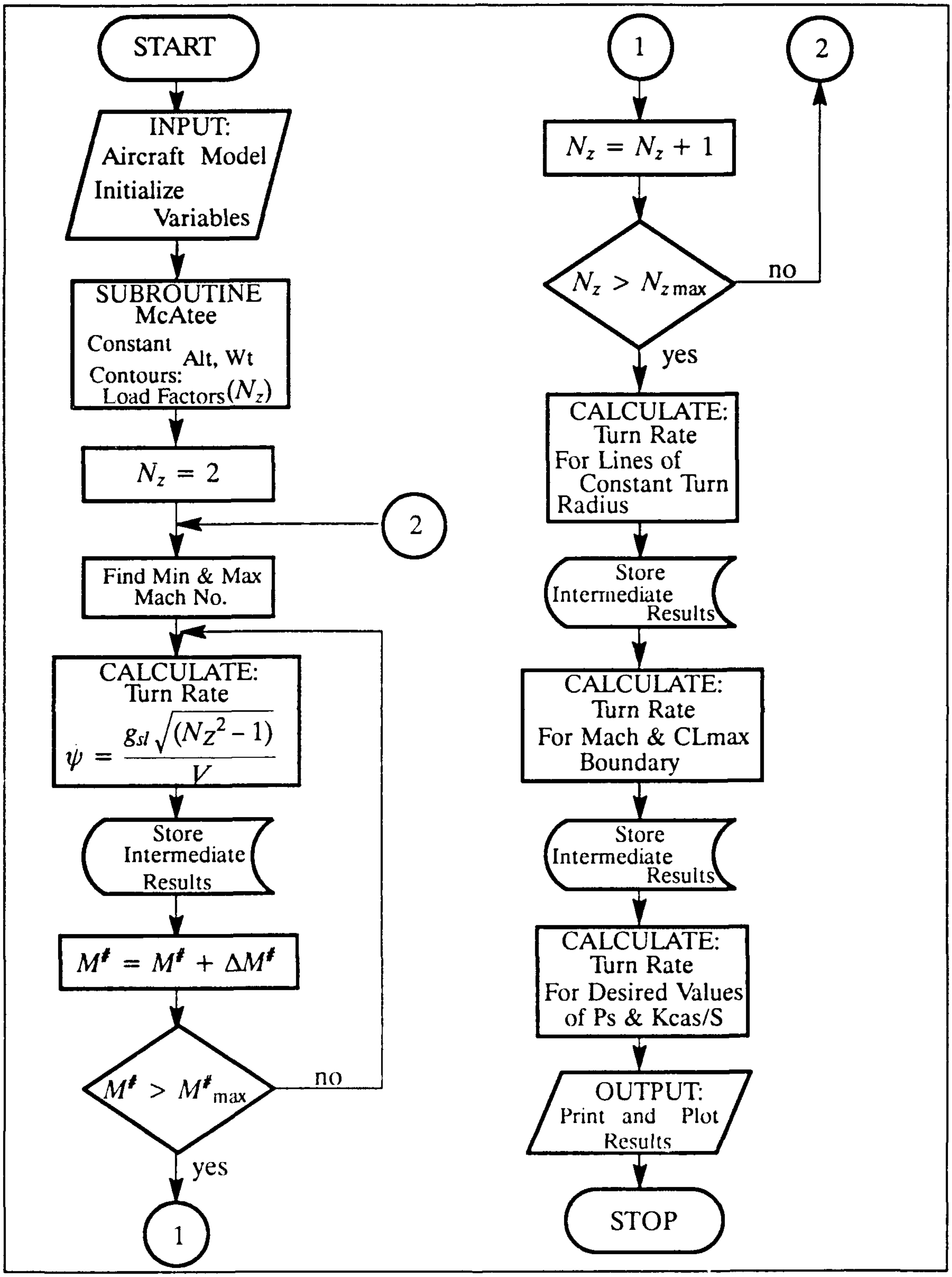


Figure 29. Algorithm for McAtee's Metrics (Turn Rate vs $M^\#$, N_Z contours)

Trajectory Simulations

In this study, the effects of the advanced and classic metrics on an aircraft's combat effectiveness were measured by trajectory simulations. The reason for using these simulations was due to the fact that trajectories are a fundamental part of the major combat effectiveness tools such as AASPEM and TAC BRAWLER. These trajectory simulations were based on the time integration of the 3-DOF formulation of the equations of motion. The input data was based on the aircraft models as described at the beginning of this chapter and the simulation results have been tabulated for further analysis.

Three basic maneuvers were modeled which attempt to represent an aircraft that is responding to an advisory aircraft. The first trajectory would be a typical high speed entry maneuver after which a slower speed fight would ensue (trajectory #2) and then finally the aircraft disengages the fight (trajectory #3) in order to regroup for another encounter. These maneuvers were also chosen in order to try to isolate the 3-DOF effects resulting from variations in the *agility* and design metrics. These maneuvers are illustrated in Figures 30 thru 32 which show the initial conditions and the output parameters that were tabulated for further analysis.

Trajectory #1 models a simple vertical loop. Although this maneuver is very basic, it can be considered to be a fundamental part of several vertical displacement maneuvers. The variables which were considered for this simulation were T/W, W/S and pitch rate (g-onset).

Trajectory #2 simulates a portion of the classic scissors maneuver. The intent of this maneuver is to minimize the radial distance in order to achieve a position advantage behind an advisory aircraft. This maneuver, like Kalviste's, is an 'open loop' maneuver which provides insight into the 'closed loop' performance using

only a single aircraft. For this study, only the T/W, W/S and roll rate were considered as variables to determine the resulting trajectory changes.

Trajectory # 3 is maximum effort acceleration maneuver. This simulation quantifies an aircraft's ability to disengage a target and attempt to regain some amount of energy lost during the engagement. The initial conditions of this maneuver are typically a very slow speed at maximum available load factor. The power setting can be either at maximum or idle thrust conditions. This maneuver provides some valuable insight into the effect of pitch authority on longitudinal speed. For this study, the T/W, W/S, pitch rate (g–onset) and power rate were considered as variables in order to determine the trajectory effects.

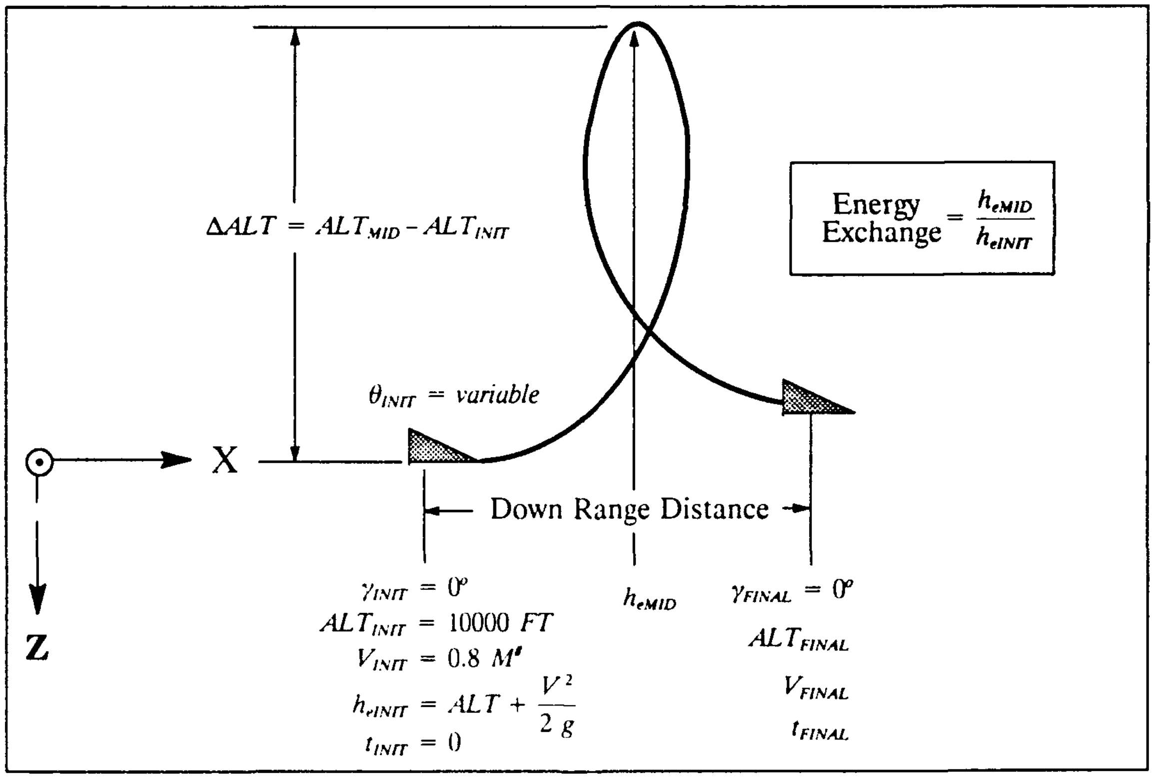


Figure 30. Trajectory # 1 —— Vertical Loop

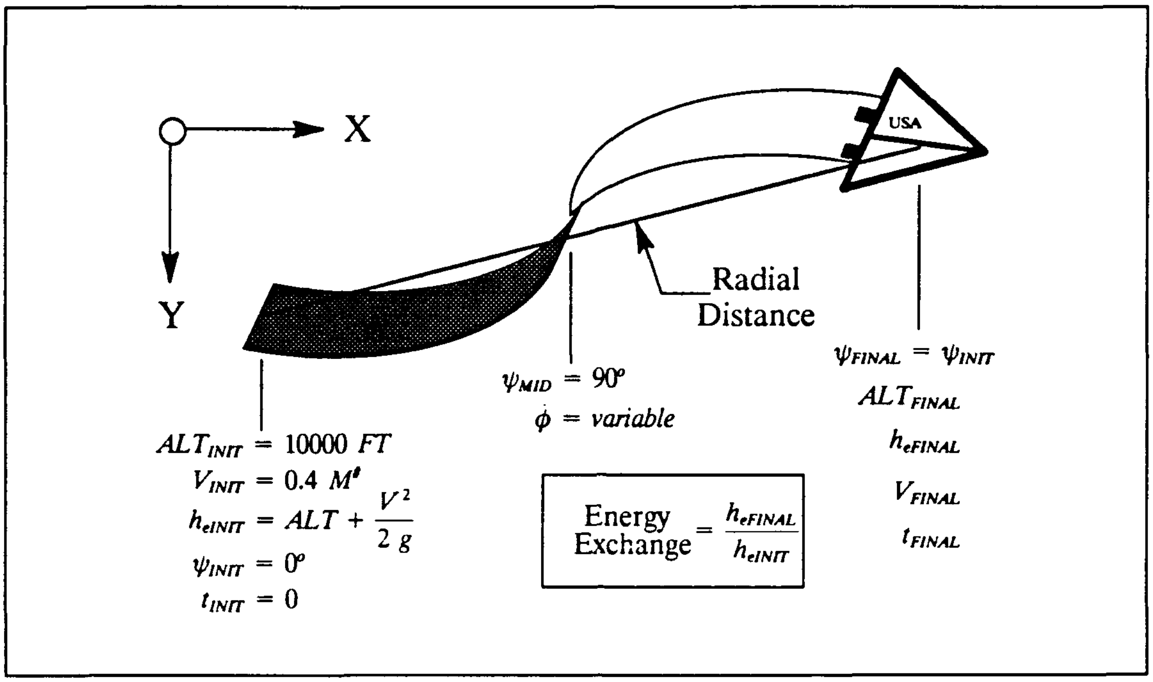


Figure 31. Trajectory # 2 — Scissors Maneuver

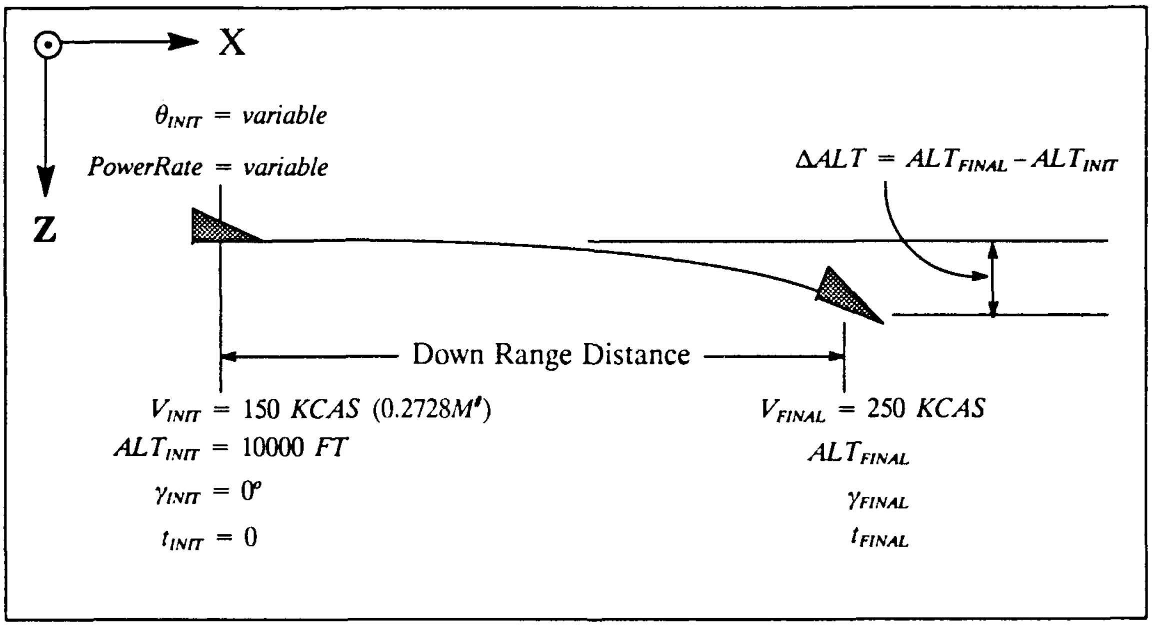


Figure 32. Trajectory # 3 — Maximum Effort Acceleration

Parametric Analyses of Advanced Metrics and Trajectory Simulations

The overall objective of this study was to quantify the relationship between the advanced performance metrics and rudimentary trajectory performance. The approach taken to quantify this relationship was to perform a parametric analysis on the metrics and trajectories using variations in T/W, W/S, roll, pitch (G-onset) and power rate. The results from the parametric analysis were then plotted to determine if any relationship between the metrics and trajectories existed. A method was then developed, shown in Figure 33, which would curve fit the results in order to quantify the existing relationships. This curve fit data was then tabulated and used in the final correlation of the results.

Assume that the data can be represented by the following linear relation

$$\bar{y} = a\bar{x}$$

where the error vector is defined by

$$a\bar{x} - \bar{y} = \bar{e} \quad , \quad \bar{e}^T = a\bar{x}^T - \bar{y}^T$$

then the minimum curve fit error can be obtained as follows

$$\frac{\delta(\bar{e}^T\bar{e})}{\delta a} = 0$$

$$\left(\text{where} \quad \bar{e}^T\bar{e} = a^2\bar{x}^T\bar{x} - a\bar{x}^T\bar{y} - a\bar{y}^T\bar{x} + \bar{y}^T\bar{y}\right)$$

$$2a\bar{x}^T\bar{x} - \bar{x}^T\bar{y} - \bar{y}^T\bar{x} = 0$$

solve for a

$$\therefore \quad a = \frac{1}{2}[\bar{x}^T\bar{x}]^{-1}[\bar{x}^T\bar{y} + \bar{y}^T\bar{x}]$$

Figure 33. Linear Curve Fit Method for the Parametric Analysis Results

Correlation Method

The correlation of the parametric results was based on a linear combination of the curve fit data and the desired trajectory results. Using this first order method, simple charts were made which allowed for a quick and simple comparison of the metrics. The overall process is illustrated in Figure 34.

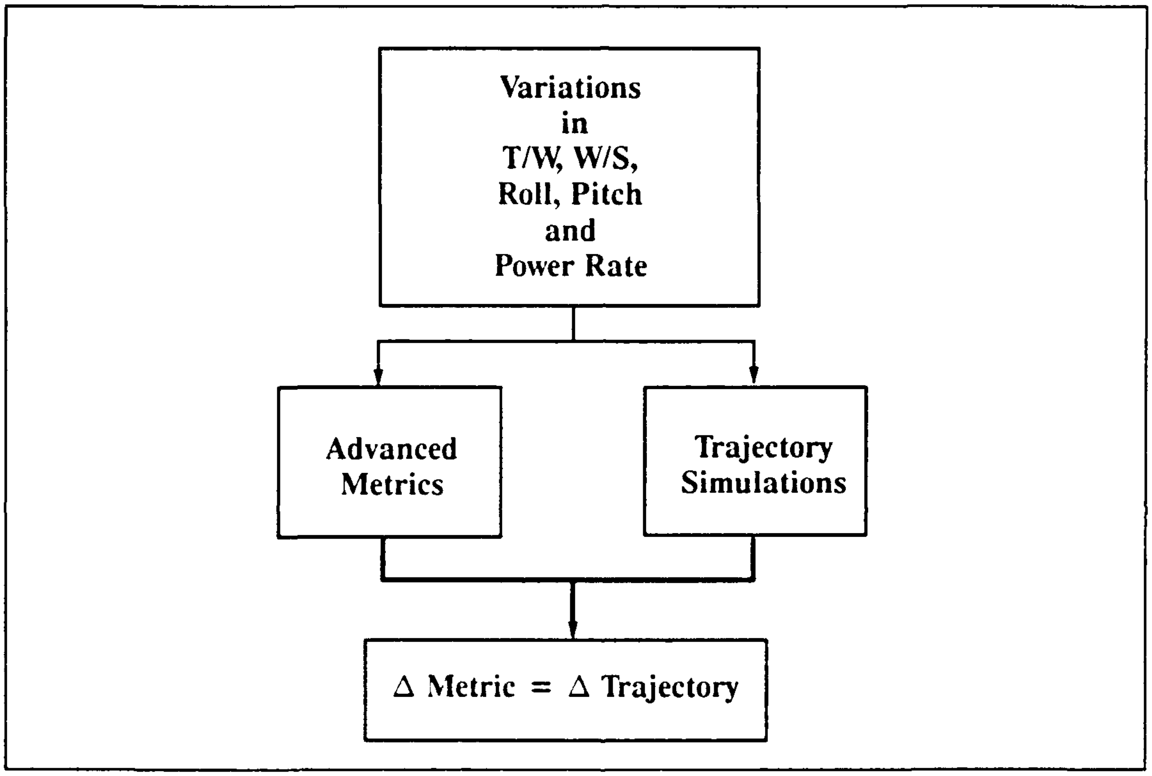


Figure 34. Correlation of Parametric Analysis Results

Summary

As illustrated at the beginning of the chapter, a process was identified and procedures were established for the investigation of the advanced performance metrics. This process led to the expansion of the performance computational capabilities which yielded several interesting relationships. The results of this study are presented in the following chapter and these relationships are discussed and further explored.

III. Results of Analyses

The presentation of results in this chapter follows the approach taken to fulfill the general objectives as outlined in Chapter 1 and shown in Figure 35. In order to accomplish the first objective, multiple plots are provided which display the results from the implementation of the algorithms that were developed for the individual metrics. Next, the second objective has been accomplished by providing plots and tabular data which were obtained from the parametric analysis. Finally, the last objective was achieved by presenting plots and data which show the correlation between the advanced metrics and the trajectories results.

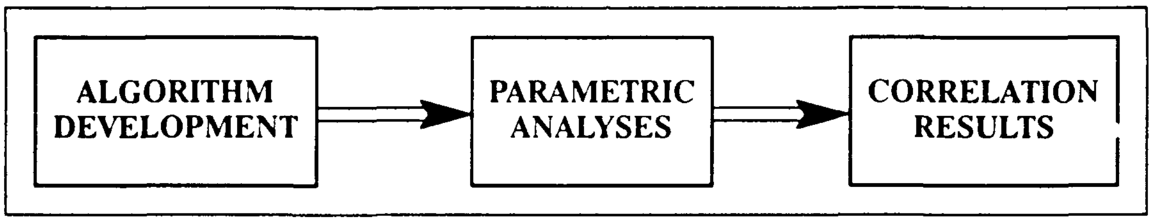


Figure 35. Research Objectives

Results from Implementation of Advanced Metrics

Most of the metrics which were described in Chapter 2 have been implemented for graphical presentation, except for Kalviste's Relative Energy State and Combat Cycle Time and Dorn's Large Amplitude Task Agility. Although graphical presentations have not been included for these metrics, their results have been tabulated for the parametric and correlation portion of this study. The plots which are shown in this section provide a small sample of the possible conditions which can be investigated. These plots, in general, provide some insight into the determination of optimal maneuvering conditions for maximum *agility*. These plots, however, make no attempt to identify the metrics which are relevant in determining combat effectiveness.

Herbst's Metrics

Figures 36 thru 38 show the results of implementing Equations 11 thru 13 from Chapter 2. These plots provide a snapshot of the aircraft's instantaneous agility for a given constant maneuver condition. In general, the plots show trends and conditions where the aircraft's agility can be maximized for optimal maneuvering. A closer look at the individual plots reveals that two optimal conditions exist, one for maximum positive agility and one for maximum negative agility. It is interesting to note that one of the maneuvering conditions coincides with the traditional best turn rate condition known as the corner velocity.

In the case of axial agility, Figure 36, this information could be used in developing maneuvers which would take advantage of the acceleration and deceleration characteristics of the aircraft. This information could also be used in the early aircraft design phase to assess the impact of the transonic drag rise on the aircraft's axial agility. The effect of the transonic drag rise is apparent in Figure 36.

The general nature of Equations 11 thru 13 allows their application to a multitude of constant maneuver conditions. The only maneuver conditions where the equations fail to apply are a vertical climb and a vertical dive where the equations become undefined due to their Euler angle definitions. The plots of these equations only apply to constant maneuver conditions due to the fact that the present form of the equations do not account for any pilot inputs of roll, pitch or throttle commands. To study these effects, the equations need to be modified in order to model the time dependant variations in the roll, pitch and throttle commands.

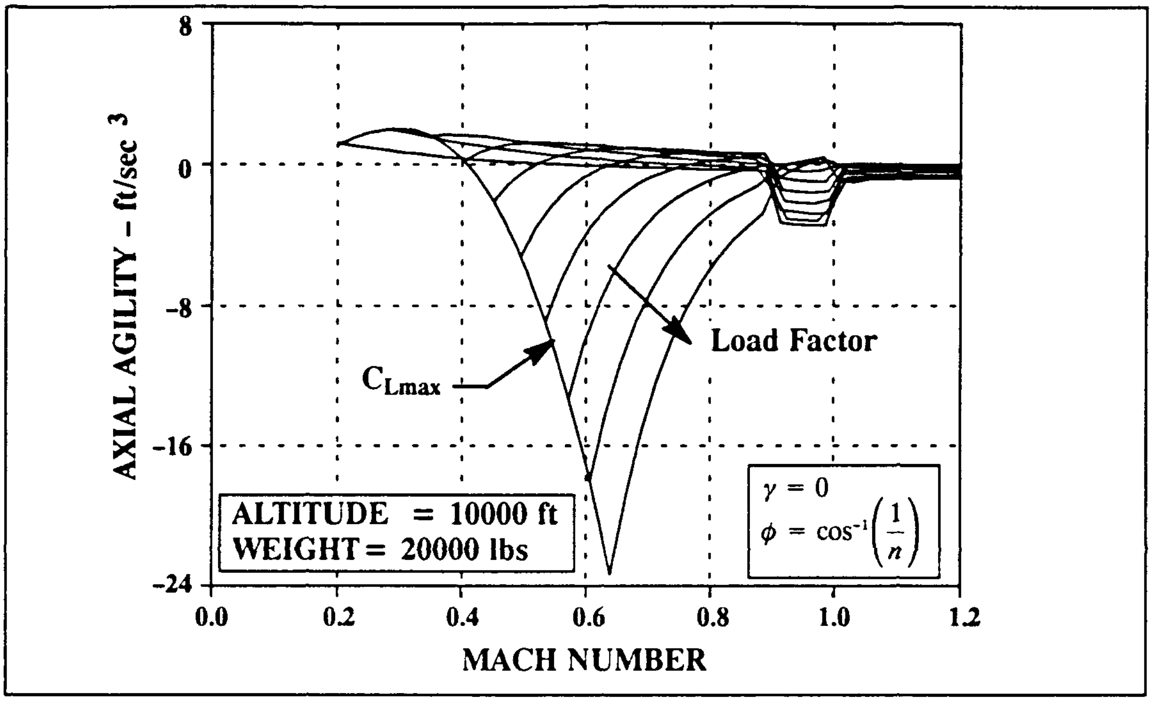


Figure 36. Herbst's Axial Agility (Coordinated, Level Turn)

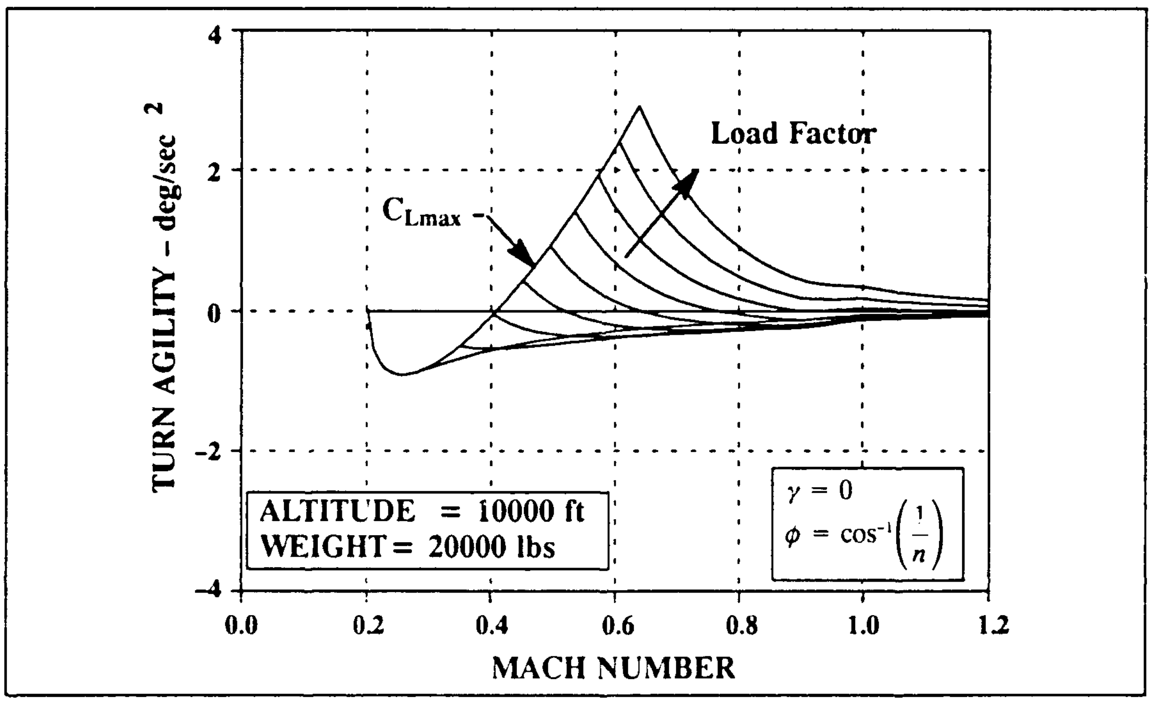


Figure 37. Herbst's Turn Agility (Coordinated, Level Turn)

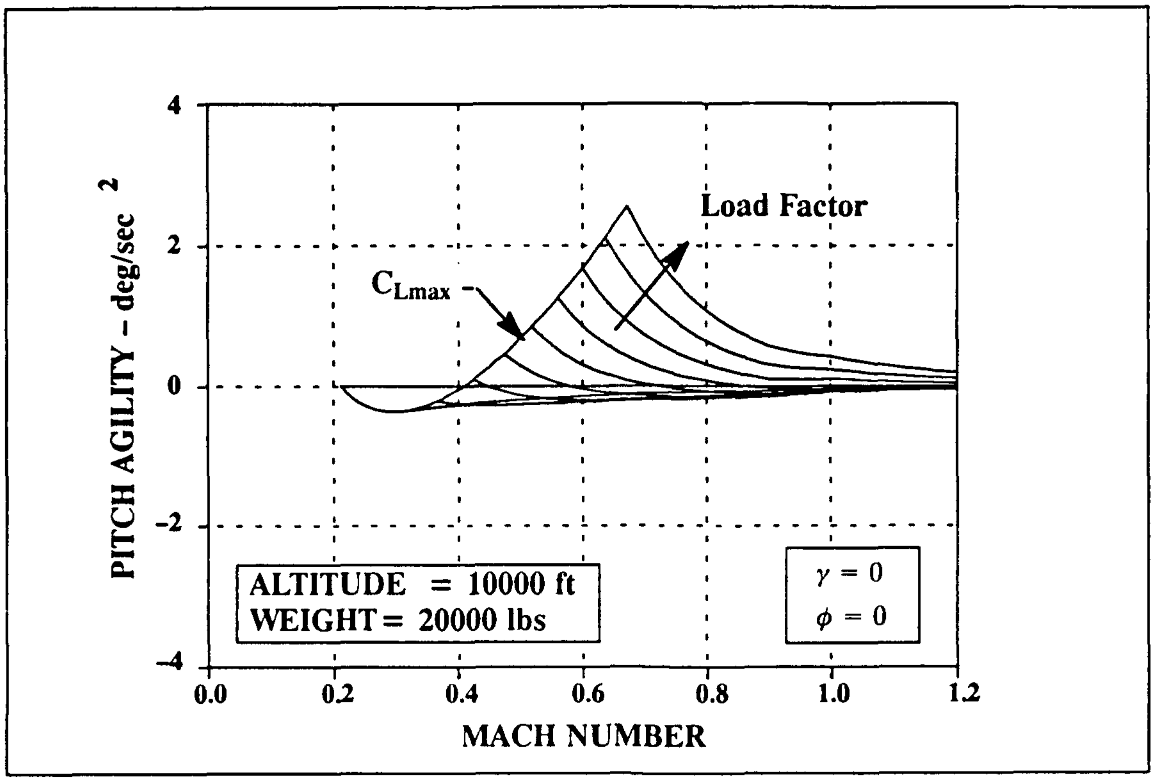


Figure 38. Herbst's Pitch Agility (Straight, Level Flight)

Eidetics' Metrics

The plots of Eidetics' torsional and axial agility metrics are presented in Figures 39 thru 45. Various crossplots of the metrics are shown in order to provide a spectrum of viewpoints which may give some insight into the utility of the metrics. The plots do show trends and conditions which could be used in determining optimal maneuvering points. For instance, Figure 39 shows that maximum torsional agility can be achieved over a range of load factors and Mach numbers. Figure 40 shows an interesting result from a plot of Ps vs Mach with turn agility contours that is the idea of sustained torsional agility. Figures 41 and 42 show the global viewpoints of these torsional agility metrics which also shows optimal maneuvering conditions. The plots for axial agility, Figures 43 thru 45, show that there is a steady increase in axial agility with increasing speed.

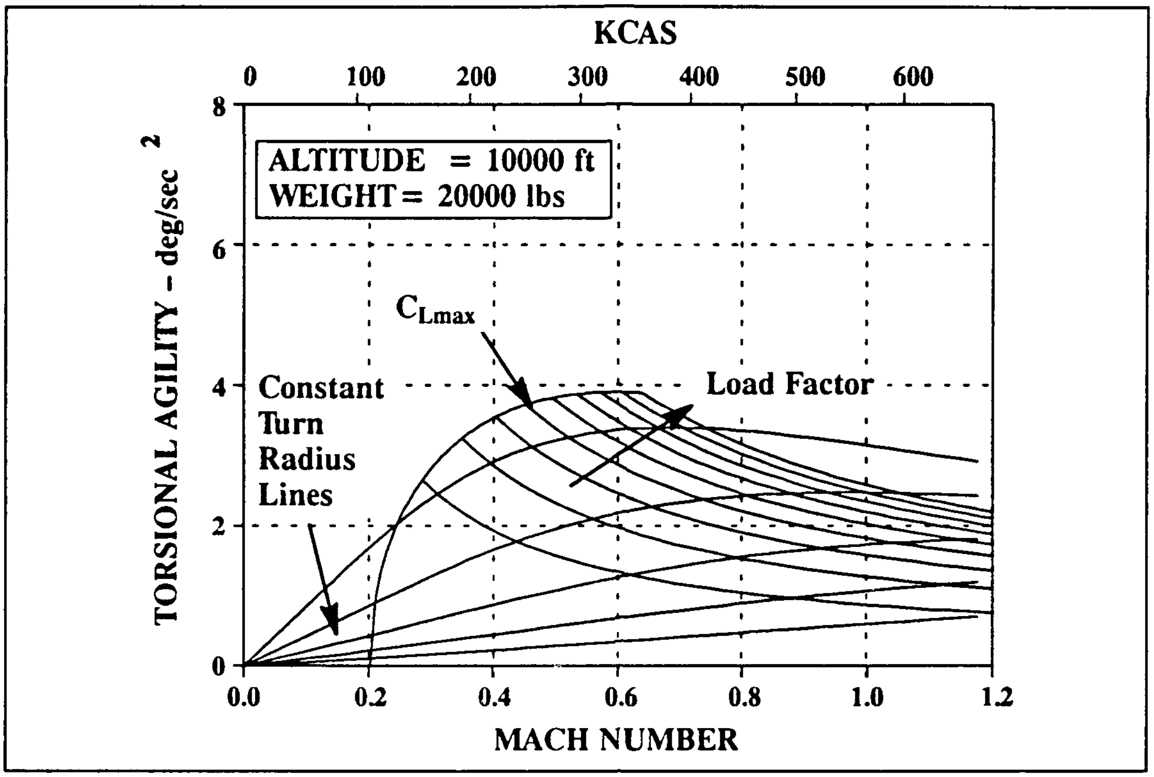


Figure 39. Eidetics' Torsional Agility (Load Factor Contours)

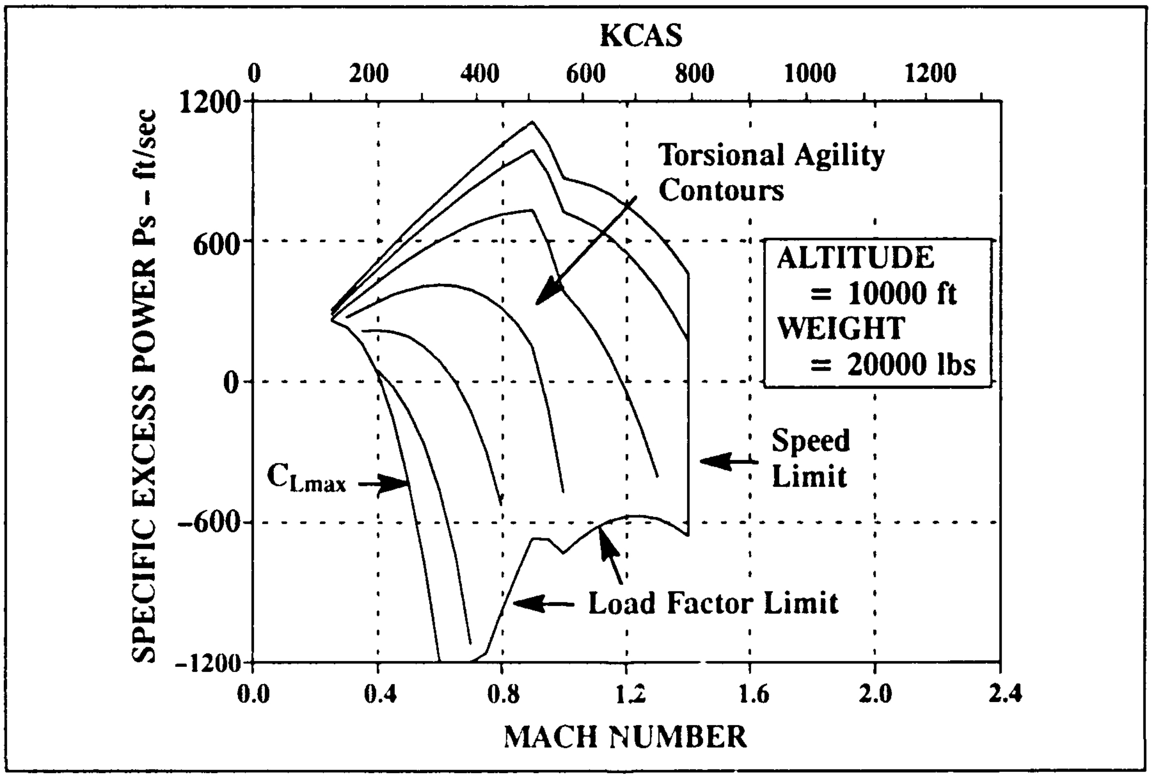


Figure 40. Eidetics' Torsional Agility Contours (Ps vs Mach)

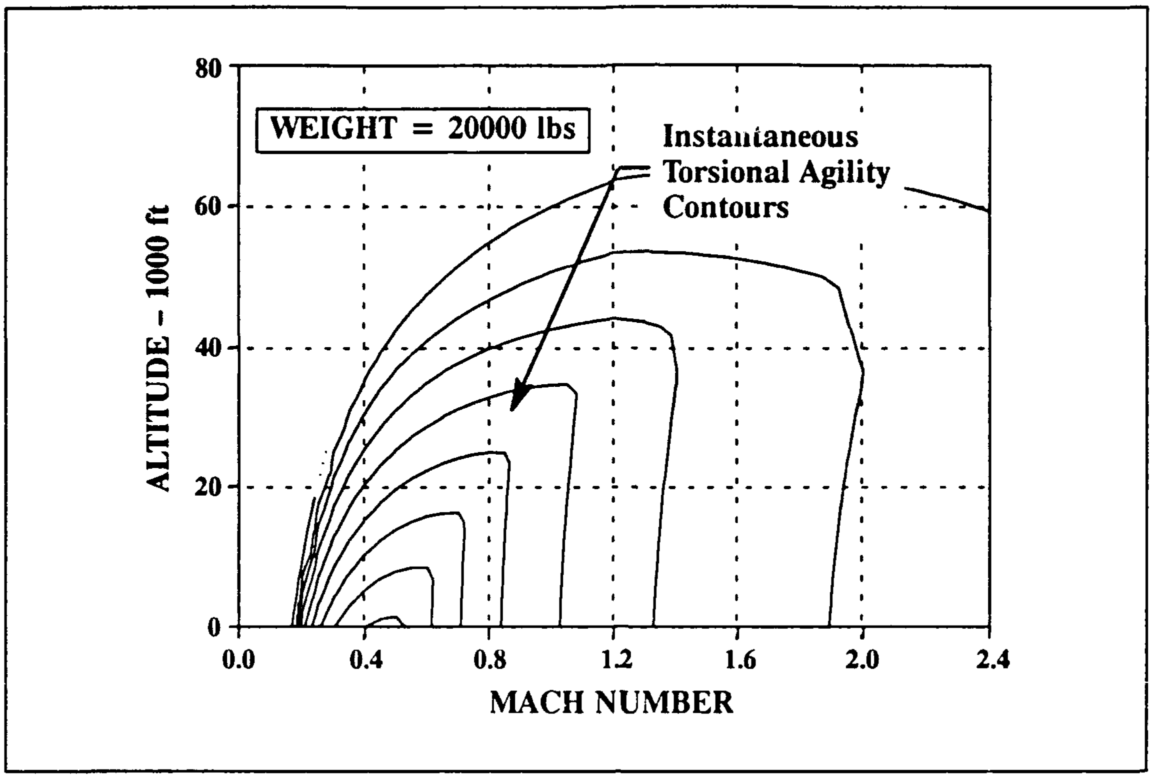


Figure 41. Eidetics' Instantaneous Torsional Agility (Altitude vs Mach)

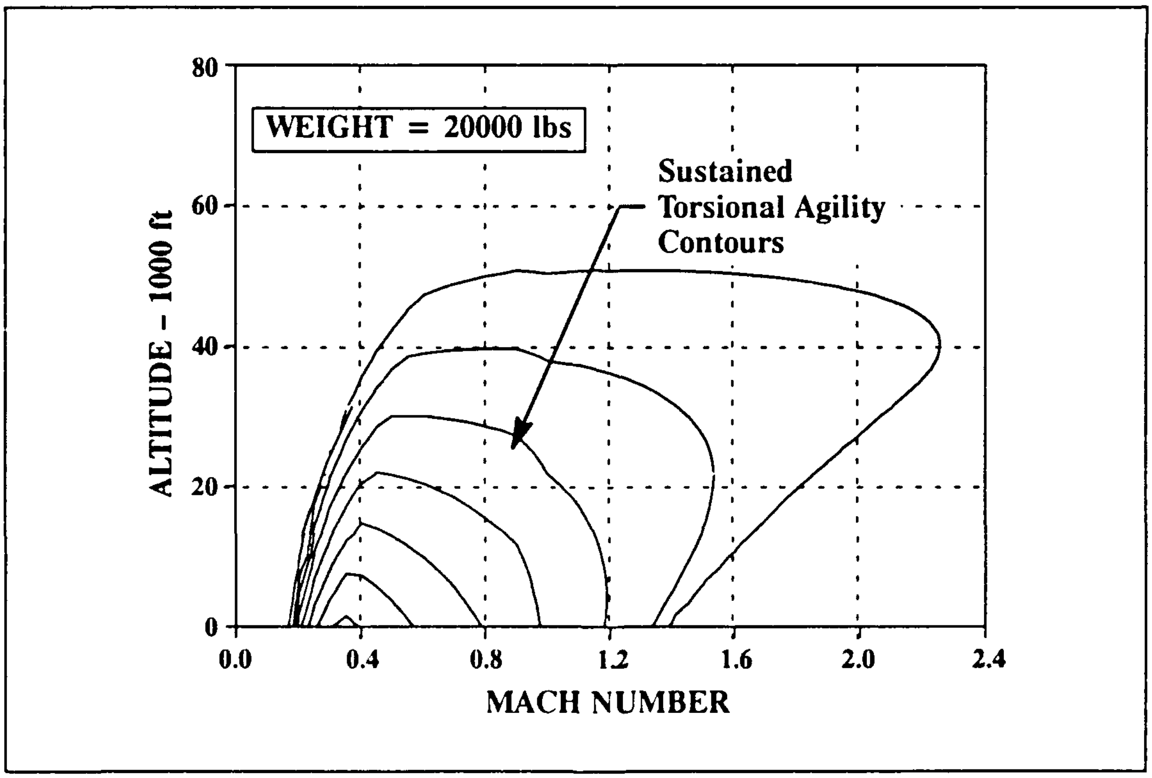


Figure 42. Eidetics' Sustained Torsional Agility (Altitude vs Mach)

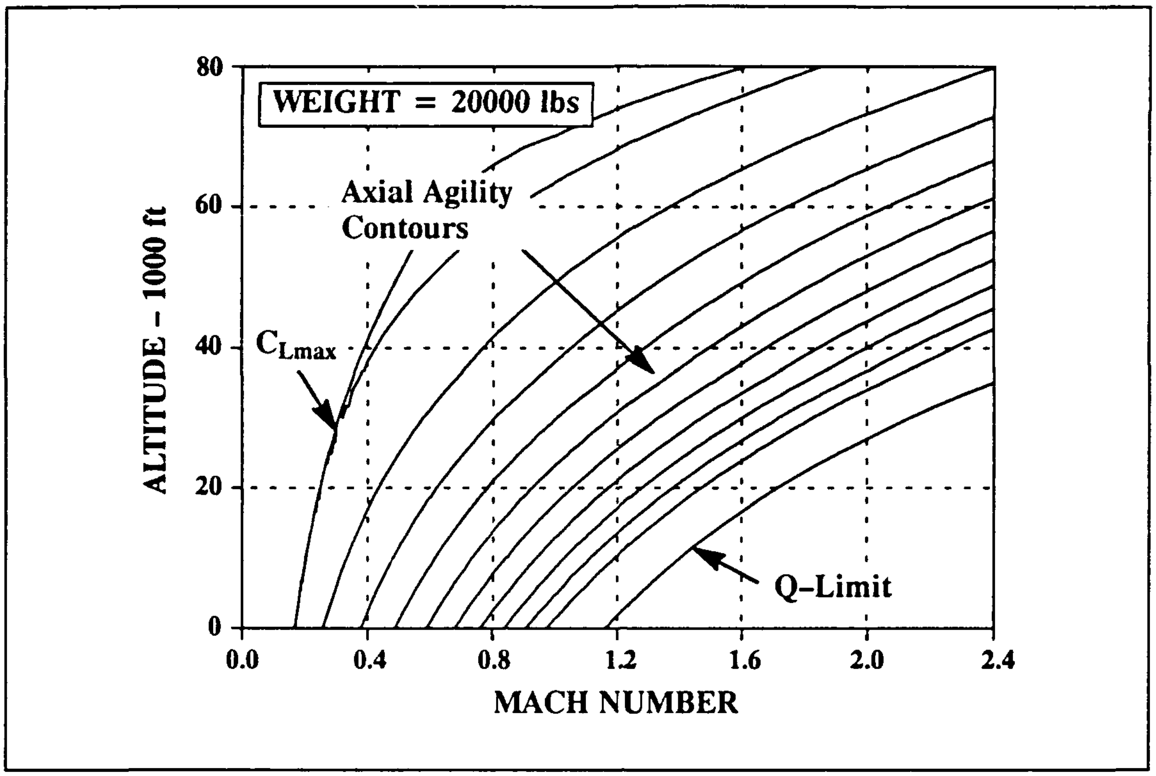


Figure 43. Eidetics' Axial Agility (Altitude vs Mach)

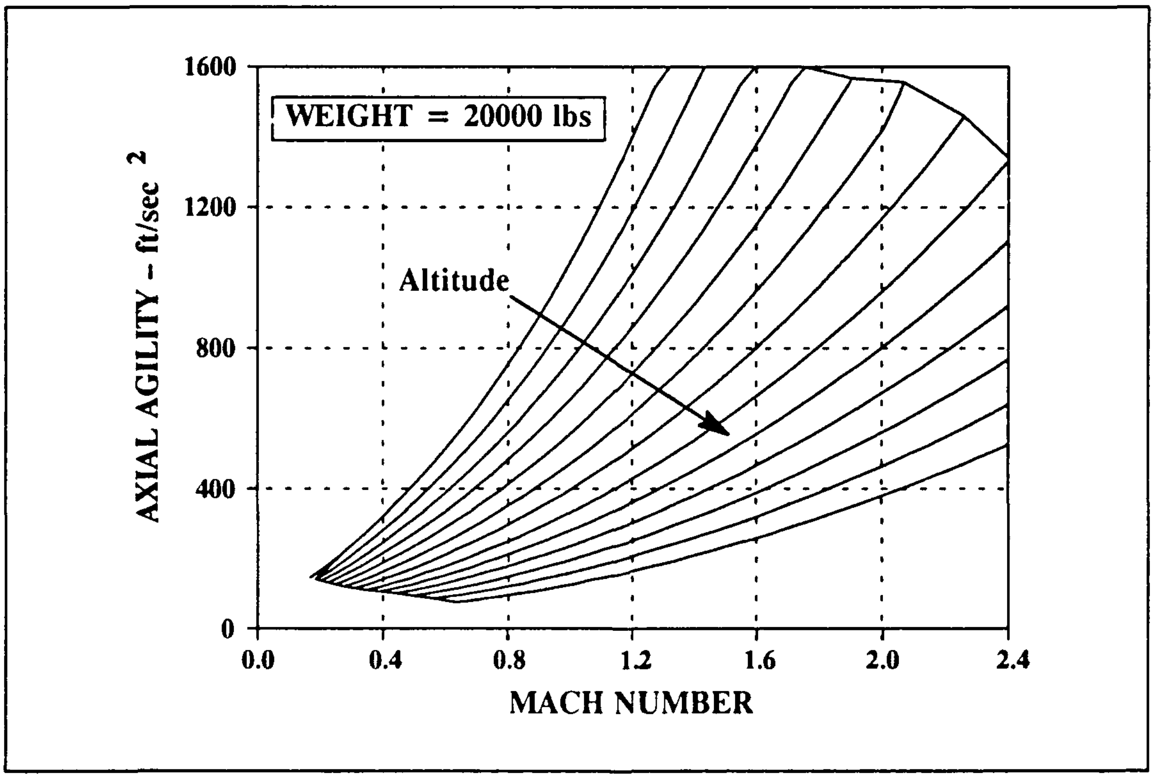


Figure 44. Eidetics' Axial Agility (Altitude Contours)

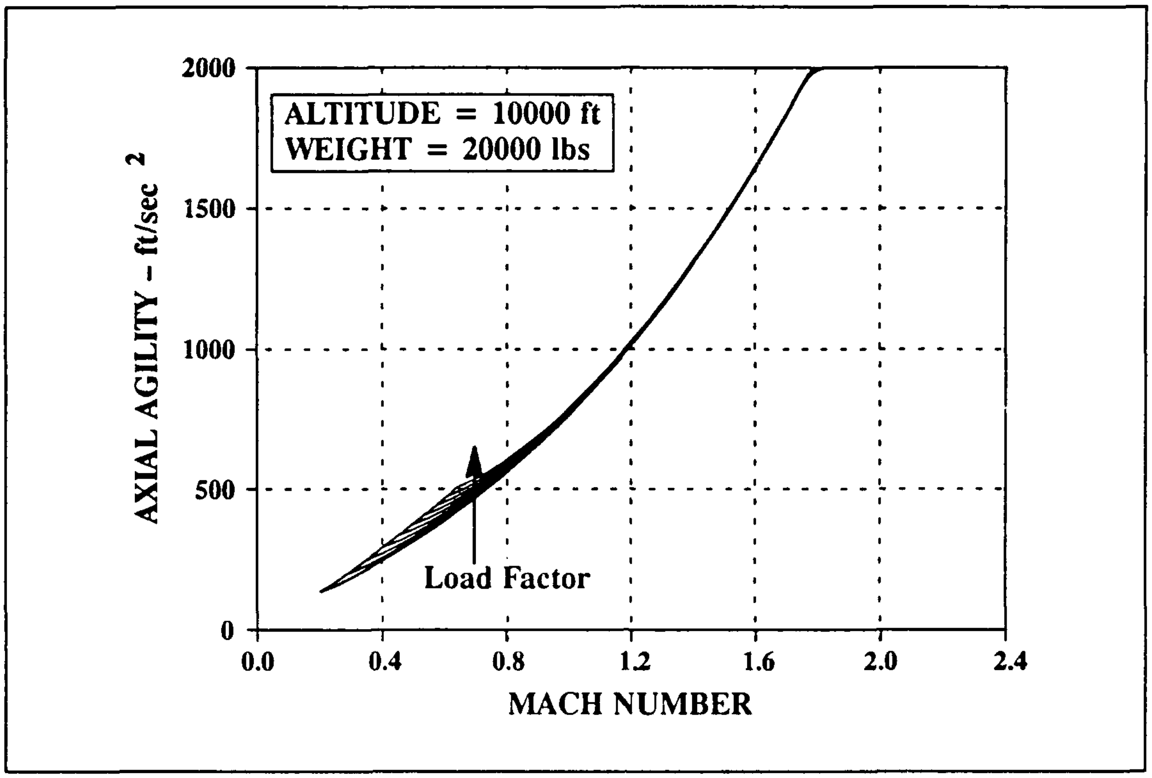


Figure 45. Eidetics' Axial Agility (Load Factor Contours)

Kalviste's Metrics

The plots of Kalviste's DT parameter, Figures 46 and 47, also show optimal maneuvering conditions which could be used in developing maneuvers and tactics. For instance, Figure 46 shows that for a given altitude, a range of initial Mach conditions exist which would provide roughly equivalent turning performance (e.g. constant DT). This plot could also be used in a comparison between two aircraft, where the contours would show the difference in the turning capabilities (e.g. Δ DT). An interesting point about the DT parameter is that it can be defined for almost any maneuver. The D part of this metric would be changed to represent the radial distance from the initial point to the end point of the maneuver and the time definition would remain the same.

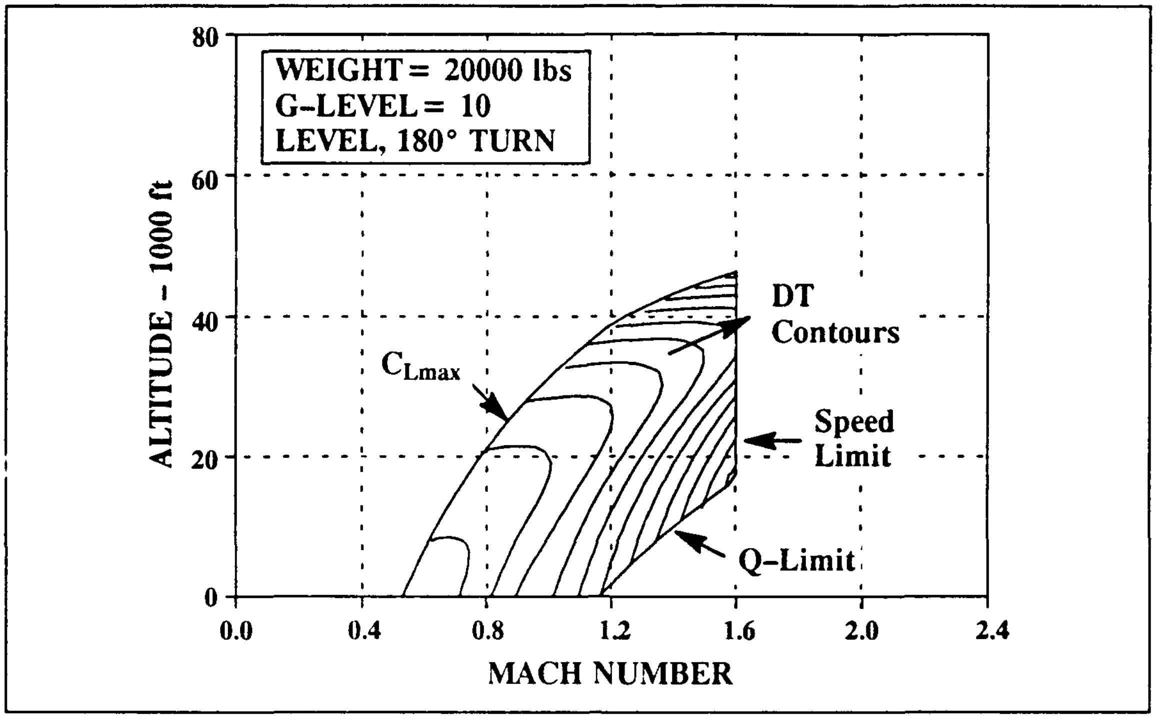


Figure 46. Kalviste's Global DT Parameter (Altitude vs Mach)

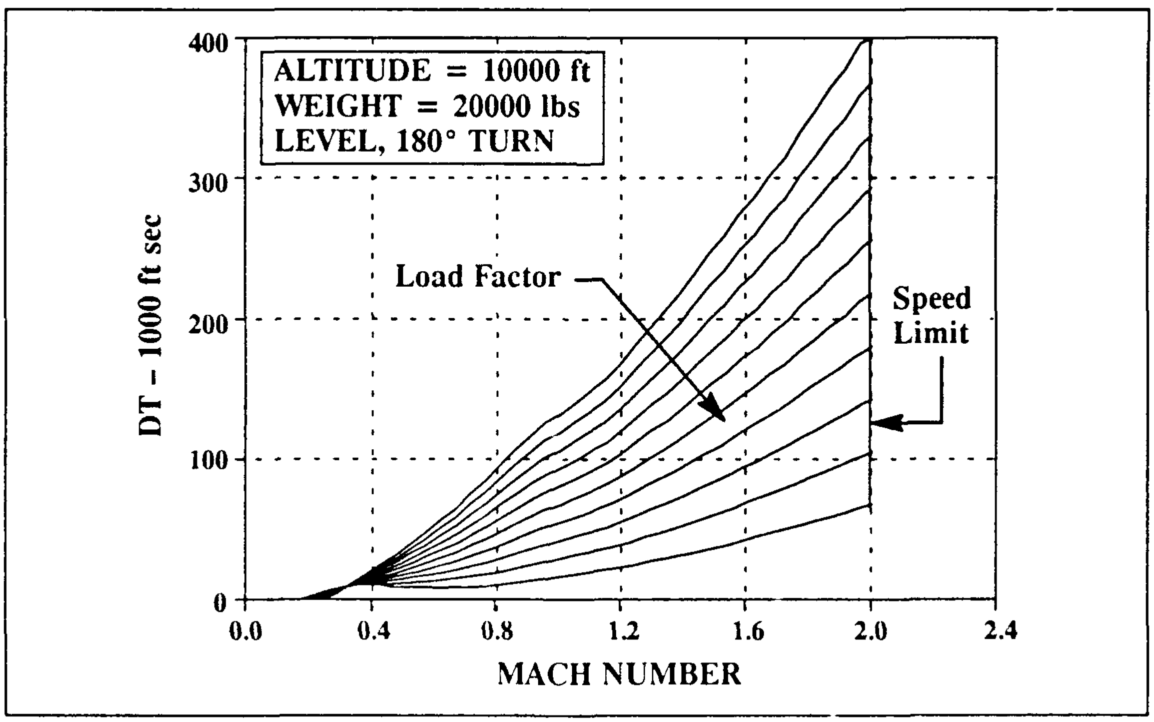


Figure 47. Kalviste's DT Parameter (Load Factor Contours)

McAtee's Metrics

Figures 48 and 49 show plots which encompass the intent of McAtee's metrics. These plots are crossplots of the information which is available from the classic turn rate and Ps plots. The benefit in this approach is that the relationship between the aircraft's turning performance and the corresponding acceleration potential is readily available for quick analysis of maneuvers and tactics. These plots eliminate the need for conversions of the Ps data in order to obtain the acceleration result. They also provide the optimum maneuvering conditions for both sustained and instantaneous turn performance. The value of this approach is currently being assessed by the U.S. Air Force which has incorporated plots similar to Figure 49 into its combat tactics manuals.

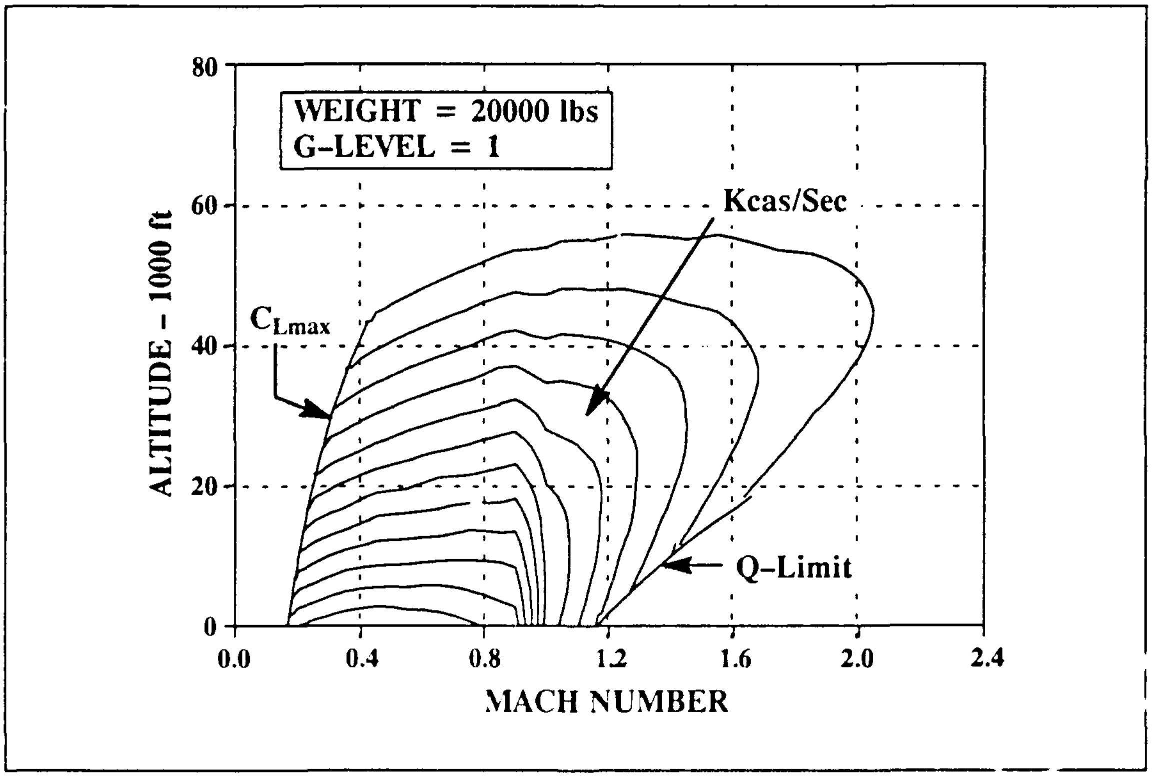


Figure 48. McAtee's 1-G Acceleration Contours (Altitude vs Mach)

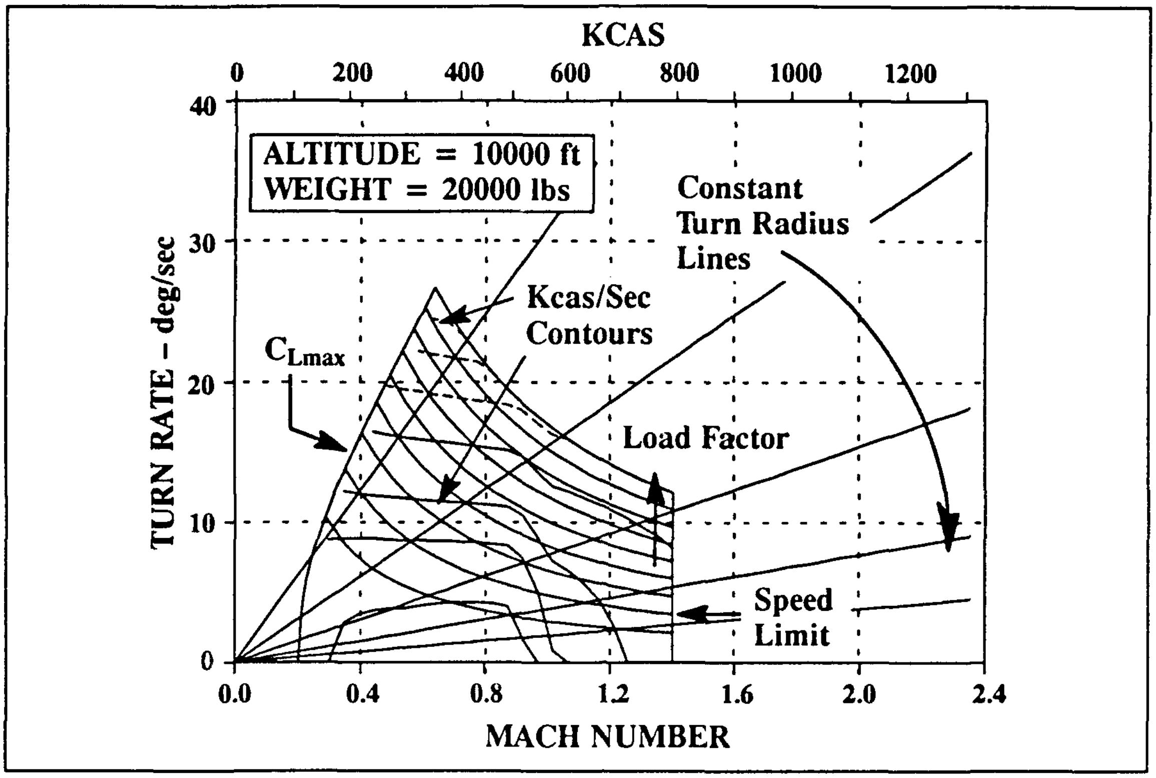


Figure 49. McAtee's Turn Rate (Bleed Rate Contours)

Parametric Analysis Results

As discussed in Chapter 2, the parametric analysis was based on variations of the design parameters T/W and W/S and variations of the control rates, roll, pitch (g-onset), and power. These variations were applied to the agility metrics and the trajectories. The results were then tabulated as shown in Table 2 and a complete set has been provided in Appendix B. These results were then plotted in order to determine if any relationship existed between the agility metrics and the parametric variables. A linear behavior was observed for most of the metrics which prompted the use of a linear curve fit to best represent the data. The results of these curve fits have been tabulated and are shown in Tables 3 thru 6. For the most part these linear curve fits were very accurate within the $\pm$ 5% region of the Δ T/W (W/S) % plots.

Table 2

Herbst's Agility Metrics
(ALT = 10000 ft, M = 0.2728)

Agility Metric	$\Delta T/W$ - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	-5	0	5	10
Turn (deg/sec^2)	-.7309	-.8109	-.8906	-.9700	-1.0492
Axial (ft/sec^3)	1.7164	1.8440	1.9628	2.0733	2.1768
Pitch (deg/sec^2)	-.3936	-.4367	-.4802	-.5225	-.5652
Agility Metric	$\Delta T/W$ - % Thrust=constant (Baseline T/W = 1.66 @ sea level)				
Turn (deg/sec^2)	-.6830	-7.846	-.8906	-1.0008	-1.1169
Axial (ft/sec^3)	1.5886	1.7709	1.9628	2.1628	2.3734
Pitch (deg/sec^2)	-.3357	-.4058	-.4802	-.5593	-.6451
Agility Metric	$\Delta W/S$ - % WT=20000 lbs (Baseline W/S = 66.7 lbs/ft^2)				
Turn (deg/sec^2)	-.9383	-.9169	-.8906	-.8598	-.8257
Axial (ft/sec^3)	2.1173	2.0420	1.9628	1.8801	1.7976
Pitch (deg/sec^2)	-.5452	-.5133	-.4802	-.4456	-.4097
Agility Metric	$\Delta W/S$ - % S = 300 ft^2 (Baseline W/S = 66.7 lbs/ft^2)				
Turn (deg/sec^2)	-1.1434	-1.0070	-.8906	-.7894	-.7008
Axial (ft/sec^3)	2.4215	2.1736	1.9628	1.7798	1.6206
Pitch (deg/sec^2)	-.6645	-.5637	-.4802	-.4091	-.3477

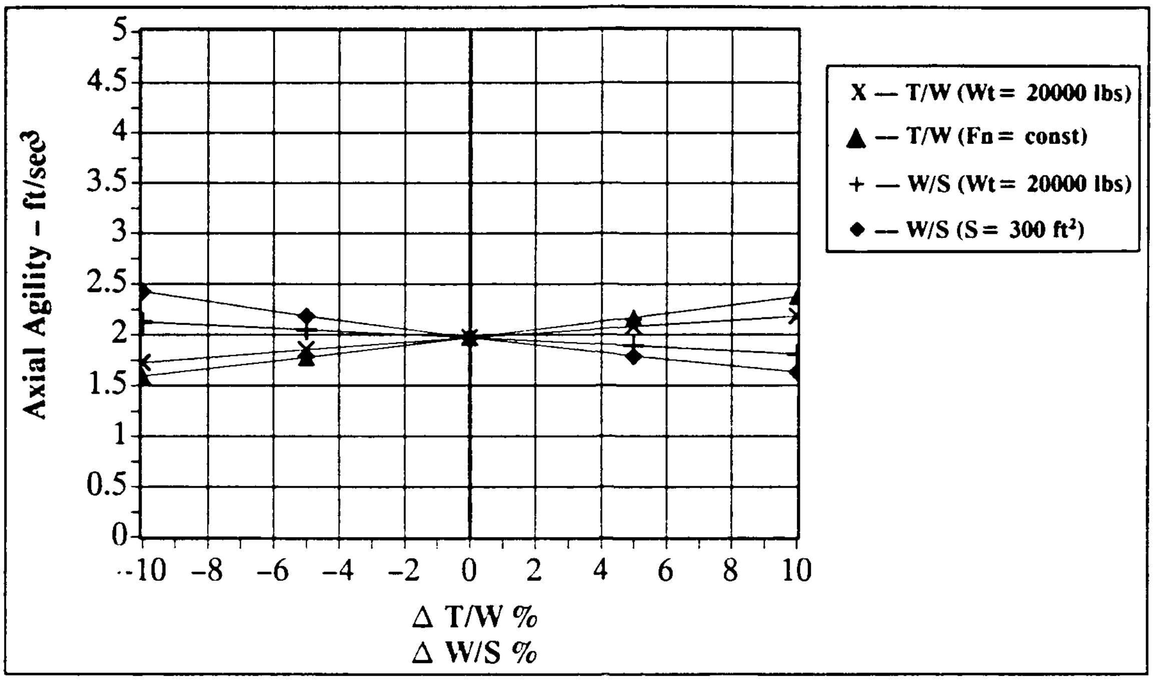


Figure 50. Herbst's Axial Agility (M = 0.2728)

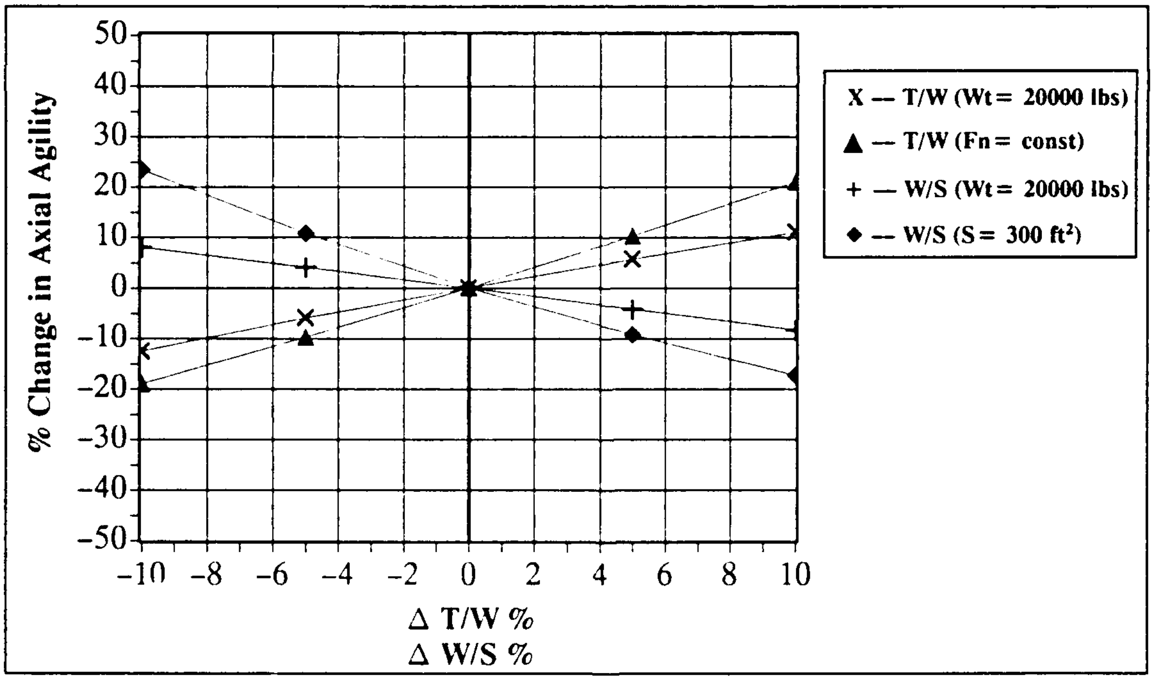


Figure 51. Herbst's Axial Agility % Change (M = 0.2728)

Table 3

Linear Curve Fits Between Metrics and Design Parameters (Traj #1)

Metrics	**{ (% ΔMetric) / (1 % ΔDesign Parameter) }**			
	T/W (Wt = 20000 lbs)	**T/W (Fn = const)**	**W/S (Wt = 20000 lbs)**	**W/S (S = 300 ft^2)**
Herbst's Axial Agility	−1.496	−4.401	2.843	4.342
Herbst's Turn Agility	−1.413	−3.225	1.806	3.230
Herbst's Pitch Agility	−1.409	−3.228	1.809	3.228
Eidetics' Torsional Agility	0.307	0.507	−0.198	−0.505
Eidetics' Axial Agility	0.788	0.849	−0.063	−0.856
Kalviste's DT Parameter	0.091	−0.376	0.487	0.248
Kalviste's V/Vc	0.525	1.285	−0.720	−1.360
Kalviste's CCT	−1.024	−1.388	0.318	1.388
Dorn's $A_{L.A.T.}$	1.655	3.231	−1.505	−3.348
McAtee's Turn Rate	0.0	0.0	0.0	0.0
McAtee's Bleed Rate	−1.412	−3.248	1.453	3.239
McAtee 's Accel Rate	1.178	0.831	0.140	−1.048
Trajectory Parameters	**{ (% ΔTraj. Para.) / (1 % ΔDesign Parameter) }**			
Distance	−0.0014	0.089	−0.076	−0.049
Mach	0.412	−0.009	0.467	0.046
Time	−0.173	−0.815	0.568	0.765
Altitude	0.027	−0.057	0.082	0.050
Energy	0.194	0.140	0.053	−0.153

Table 4

Linear Curve Fits Between Metrics and Design Parameters (Traj #2)

Metrics	{ (% ΔMetric) / (1 % ΔDesign Parameter) }			
	T/W (Wt = 20000 lbs)	**T/W (Fn = const)**	**W/S (Wt = 20000 lbs)**	**W/S (S = 300 ft^2)**
Herbst's Axial Agility	22.789	1.962	21.542	-1.993
Herbst's Turn Agility	23.019	2.054	21.551	-2.096
Herbst's Pitch Agility	23.055	2.386	21.386	-2.429
Eidetics' Torsional Agility	0.0	0.731	-0.732	-0.732
Eidetics' Axial Agility	0.909	1.000	-0.091	-1.008
Kalviste's DT Parameter	-0.512	-2.176	1.414	2.095
Kalviste's V/Vc	0.476	0.551	-0.073	-0.553
Kalviste's CCT	-0.885	-1.097	0.212	1.044
Dorn's $A_{L.A.T.}$	4.588	3.319	1.080	-3.247
McAtee's Turn Rate	0.0	1.070	-1.078	-1.078
McAtee's Bleed Rate	23.015	0.997	22.199	-1.027
McAtee's Accel Rate	1.119	1.131	-0.012	-1.139
Trajectory Parameters	{ (% ΔTraj. Para.) / (1 % ΔDesign Parameter) }			
Distance	-0.081	-0.698	0.617	0.652
Mach	0.331	-0.236	0.568	0.232
Time	-0.288	-0.423	0.154	0.365
Altitude	0.101	0.168	-0.067	-0.163
Energy	0.194	0.059	0.134	-0.056

Table 5

Linear Curve Fits Between Metrics and Design Parameters (Traj #3)

Metrics	{ (% ΔMetric) / (1 % ΔDesign Parameter) }			
	T/W (Wt = 20000 lbs)	**T/W (Fn = const)**	**W/S (Wt = 20000 lbs)**	**W/S (S = 300 ft^2)**
Herbst's Axial Agility	1.172	1.999	-0.817	-2.033
Herbst's Turn Agility	1.787	2.434	-0.634	-2.477
Herbst's Pitch Agility	1.787	3.216	-1.411	-3.283
Eidetics' Torsional Agility	0.0	1.250	-1.252	-1.252
Eidetics' Axial Agility	0.918	1.00	-0.082	-1.009
Kalviste's DT Parameter	-0.600	-2.263	1.560	2.195
Kalviste's V/Vc	0.502	0.542	-0.044	-0.545
Kalviste's CCT	-0.435	-1.113	0.609	1.095
Dorn's $A_{L.A.T.}$	-1.785	3.411	-5.437	-3.498
McAtee's Turn Rate	0.0	1.438	-1.447	-1.447
McAtee's Bleed Rate	1.788	1.000	0.793	-1.009
McAtee 's Accel Rate	1.185	1.225	-0.058	-1.255
Trajectory Parameters	{ (% ΔTraj. Para.) / (1 % ΔDesign Parameter) }			
Distance	-0.829	-0.835	0.0052	0.714
Gamma	-0.829	-0.829	0.0	0.745
Time	-0.872	-0.872	0.0	0.769
Altitude	0.0514	0.0518	0.0	-0.0446

Table 6

Linear Curve Fits Between Metrics and Control Rates (Traj #1-3)

Metrics	{ (% ΔMetric) / (1 % ΔControl Rate) }			
	Trajectory #1 (G-onset Rate)	Trajectory #2 (Roll Rate)	Trajectory #3 (G-onset Rate)	Trajectory #3 (Power Rate)
Eidetics' Torsional Agility	-	1.00	-	-
Eidetics' Axial Agility	-	-	-1.280	-1.280
Eidetics' Pitch Agility (1 sec avg)	-0.880	-	-0.425	-0.425
Eidetics' Pitch Agility (5 sec avg.)	-0.126	-	-2.263	-2.263
Trajectory Parameters	**{ (% ΔTraj. Para.) / (1 % ΔControl Rate) }**			
Distance	-0.397	-0.098	-0.245	0.145
Mach/Gamma	-0.039	0.116	0.863	0.387
Time	-0.080	-0.235	-0.258	0.213
Altitude	-0.016	-0.074	-0.033	-0.024
Energy	-0.029	-0.023	-	-

Correlation Results

The linear behavior of the parametric results provided the basis for the correlation between the agility metrics and the trajectory results. Using the linear curve fit data, Tables 3 thru 6 from the previous section, correlation results were calculated as shown in Equation 14, which provides the desired relationship between the individual metrics and the operationally significant trajectory parameters. Plots of these relationships were then made as shown in Figures 52 thru 54, which show the required amount of change in the agility metrics to get a

fixed change in the operationally significant trajectory parameters. A complete set of these plots has been provided in Appendix C. As in the previous section, the correlation results have been provided for variations of both the design parameters and the control rates.

$$\begin{matrix} \% \ \Delta \mathit{Herbst's} \\ \mathit{Axial\ Agility} \end{matrix} = \left(\frac{-1.49\% \ \Delta \ \mathit{HAA\ metric}}{\% \ \Delta \ T/W} \right) \left(\frac{\% \ \Delta \ T/W}{-.17 \ \% \ \Delta \ \mathit{Traj}} \right) (-1.0 \ \% \ \Delta \ \mathit{Traj}) \qquad \textbf{(14)}$$

The plots for the design parameters have all the metrics on single plot which shows the interrelationships between the individual metrics and the trajectory parameters. This approach of putting all of the metrics on a single plot was intended to show any inconsistencies which may have resulted from the correlation method. One obvious problem which is apparent in these plots is that not all of the metrics can be applied to the various trajectories. For instance in Figure 52, Kalviste's metrics (3a–3c) should not be applied to the vertical loop trajectory due to the fact that they are only defined for a 180°, level turn. For that matter, only a couple of the metrics should be applied to the various trajectories. In the case of trajectory #1, Herbst's axial and pitch metrics, McAtee's bleed rate metric and the design metrics T/W and W/S should be applicable. Figure 53 shows this case where only those metrics which are applicable have been plotted.

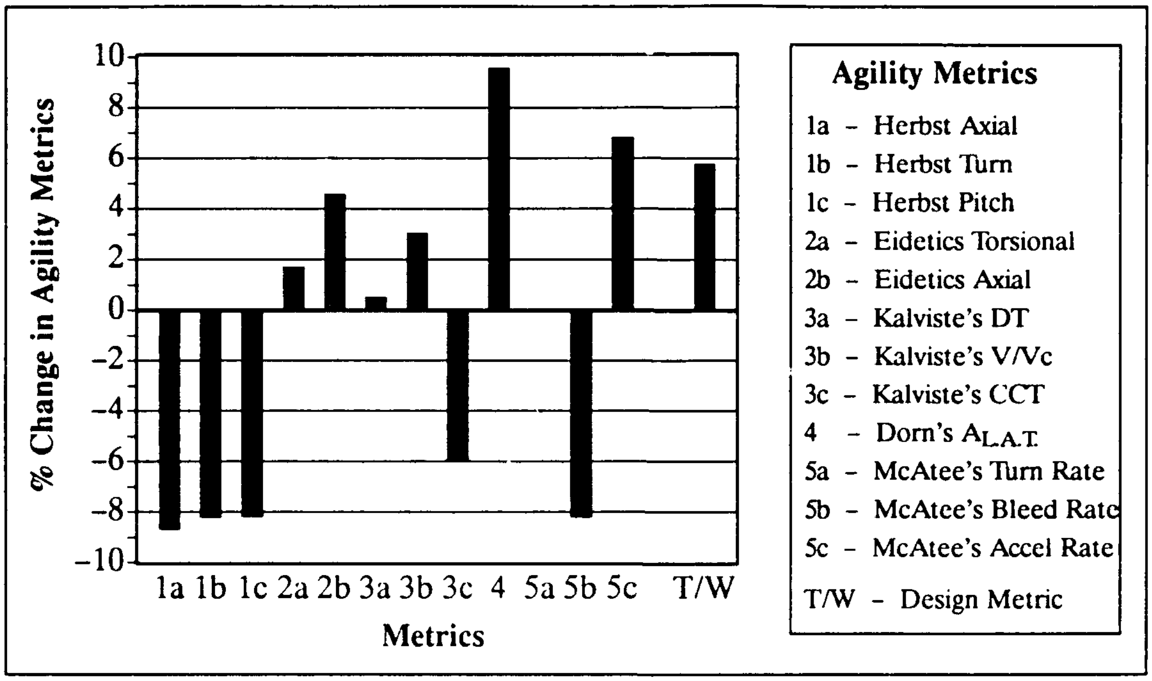


Figure 52. [Traj # 1] -1% Change in Midpoint Time (ΔT/W%, Wt=20000 lbs)

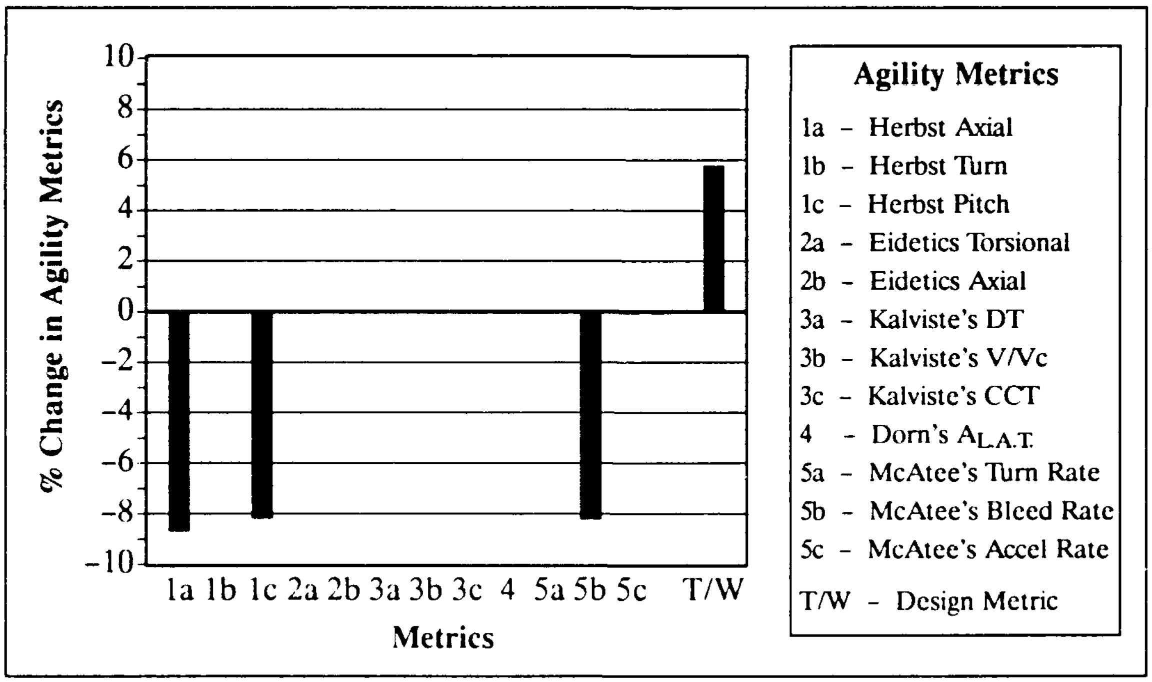


Figure 53. [Traj # 1] -1% Change in Midpoint Time (ΔT/W%, Wt=20000 lbs)

The plots for the control rate variations, as shown in Figure 54, only show Eidetics metrics in relation to the trajectory parameters. This is due to the fact that the other metrics do not account for any variations in the roll, pitch (G-onset) and power rates. A complete set of these plots have also been provided in Appendix C. As in the case of the design metrics some of these control rate metrics only apply in certain trajectories. Figure 54 shows those metrics which apply for the various trajectories.

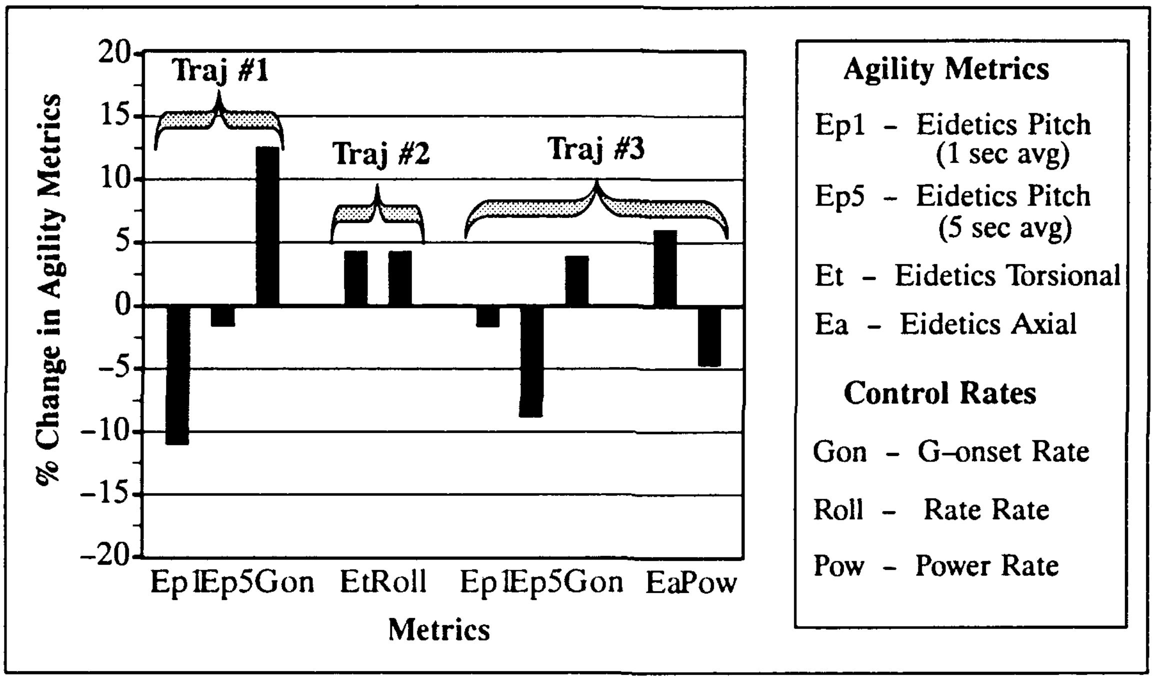


Figure 54. [Traj #1-3] -1% Change in Maneuver Time

Discussion

The results presented in this section and in Appendices B and C provide a starting point for a much needed analysis and comparison of the present advanced metrics. The tools for this comparison are in place, requiring only minor modifications for a more thorough presentation of results. The work thus far has provided some limited insight into the strengths and weaknesses of each of these

metrics. This insight is given in the following comments regarding these metrics and the correlation method used for this study.

The Herbst' equations represent instantaneous levels of agility. They can be applied for constant maneuvers as well as dynamic (piloted) maneuvers. The equations can be implemented in trajectory simulations in order to track the agility levels throughout the maneuvers. They can also be used to analytically study the impacts on agility due to design changes.

The Eidetic's metrics can be readily quantified for any aircraft and appear to provide rough estimates of the aircraft's combat effectiveness. However, in retrospect, the metrics provide inconclusive results with regard to combat effectiveness. For example, the torsional agility of an F-5 is better than that of an F-15. Which aircraft is better? Also, these metrics provide little value to design iterations because of the combined effects inherent to these metrics. It is difficult to discern the important design parameters as related to combat effectiveness, for example, in torsional agility, is a dominant aircraft better because of greater turn rate or better loaded roll capability? The combined effects of these metrics also give misleading implied relationships with acceleration. For example, torsional agility has dimensional units of deg/sec^2 and axial agility has units of ft/sec^2. Neither metric has any relationship with acceleration.

Kalviste's relations appear to be useful in design iterations as well as aircraft comparisons. These metrics are based on the combat significant parameters which pilots commonly discuss during debriefings of engagement scenarios. A strength of these metrics is the capability of expanding the metrics definition to represent almost any maneuver. The only apparent problem with these metrics is that they can not be used to analytically determine the effects of design changes.

Dorn's relationships encompass all of Kalviste's metrics into one parameter in order to show the combined effects. This approach appears to be useful; however, there is a major flaw with the relationship as defined. The problem is due to the energy consumption term. For instance, if an aircraft gains energy through a maneuver, it has negative agility according to Dorn's metric. Also, if an aircraft sustains the maneuver (i.e. no energy gained or lost) it has infinite agility by definition. Aside from this problem, the metric combines too much information into one metric which makes it almost impossible to use in design or comparison studies.

McAtee's metrics provide another viewpoint of the classic metrics. They improve the user's (designer, evaluator, pilot) ability to apply the classic metric to achieve a more optimum aircraft design or combat effective maneuver.

Relating the individual metrics back to Dorn's "3 time scales of agility" combined with the insight developed by this research effort, the following statements appear to be evident; 1) instantaneous agility as expressed by Herbst's metrics, appears to be a "true agility" representation; 2) the small amplitude task agility characterized by Eidetics metrics seems to be more appropriately called "maneuver-agility" and 3) the large amplitude task agility shown by Kalviste and McAtee is nothing more than time integrated maneuverability.

There is a potential for much to be learned about the metrics with the results available from this research. Levels of "good" agility will have to be determined in order to better understand the relations between the advanced metrics and the design metrics. The correlation method results must be filtered in order to show the extent to which the metrics apply to various combat maneuvers. Finally, the surviving metrics need to be accepted by the designers, the evaluators, and ultimately the pilots.

IV. Conclusions and Recommendations

Conclusions

The goals of this research effort were to; 1) implement the advanced metrics into a single analysis tool; 2) study the relationship between the advanced metrics and the design metrics and 3) determine the ability of the metrics to quantify trajectory performance. These goals were met with limited success.

Computer code was developed which was used to study the various metrics. This mainframe based code readily quantifies and displays the results of the advanced metrics for any aircraft with trimmed aerodynamic and installed propulsion data. However, further code development work is required to include the complete set of advanced metrics and to account for pilot inputs of pitch, roll and throttle commands.

Results from the comparison of the advanced metrics and the design metrics showed that a linear relationship between the metrics existed for the most part. This data has been made available in Appendix B for further analysis. The linear relationships were then used as the basis of the correlation part of the study.

A correlation method was used to quantify the relation of the advanced metrics to an aircraft's trajectory performance. The results showed that most of the advanced metrics could only be applied to a very limited number of trajectories. For example, Eidetic's torsional agility metric could be applied only to level turn maneuvers because of its basis on the classic metric, turn rate. This inability of the advanced metrics to be applicable to a variety of combat maneuvers precludes them from being able to determine an aircraft's overall combat effectiveness individually. As with the classic metrics, combinations of the advanced metrics may be successful in providing this measure of an aircraft's ultimate utility.

Recommendations

It is recommended that the metric quantification code be further developed to include the rest of the advanced metrics as well as new code which could be used to calculate and present performance difference calculations for the various metrics.

It is also recommended that the available data in Appendices B and C be further studied and supplemented in order to more fully understand the relationships between the advanced metrics, design metrics and an aircraft's trajectory performance.

Appendix A: Derivation of Herbst's Agility Equations

This appendix provides two different approaches which result in the Herbst agility relations and the relations as derived from the first inertial derivative of Newton's 2nd Law of Motion.

Herbst's Agility Metrics

Let

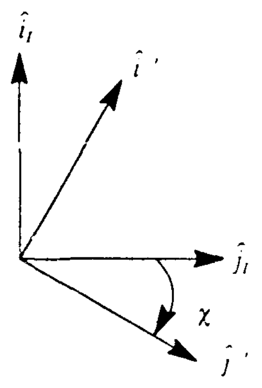
$$\vec{V} = V\,\hat{i} \tag{15}$$

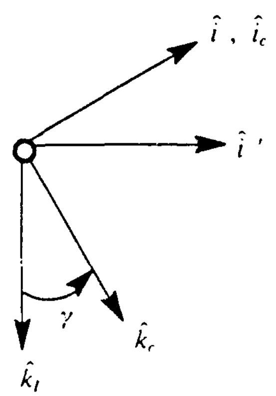
where $\hat{i}$ is the body x axis

Define two rotations, χ from the north to the present heading and γ from horizontal to the X axis of the body. In the coordinate system used, the $\hat{i}_c = \hat{i}$ and the $\hat{j}_c$ axis is horizontal to the right and $\hat{k}_c$ is generally pointed down. The roll rotation was not completed to get to the usual wind axis, since there is no roll of the C frame with respect to the I frame.

$$\hat{\omega}^{CI} = \dot{\chi}\,\hat{k}_I + \dot{\gamma}\,\hat{j}_C \tag{16}$$

where





or written in the C frame

$$\overline{\omega}^{CI} = -\dot{\chi}\,\sin\gamma\;\hat{i}_C + \dot{\gamma}\;\hat{j}_C + \dot{\chi}\,\cos\gamma\;\hat{k}_C \tag{17}$$

now let

$$\overline{\omega} = \dot{\gamma}\;\hat{j}_C + \dot{\chi}\,\cos\gamma\;\hat{k}_C \tag{18}$$

and define another coordinate frame such that

$$\overline{\omega} = \omega\;\hat{k}_W \qquad \text{and} \qquad \hat{i}_W = \hat{i}_C = \hat{i}$$

then

$$\overline{\omega}^{CI} = -\dot{\chi}\,\sin\gamma\;\hat{i}_C + \omega\;\hat{k}_W \tag{19}$$

Now for the inertial derivative of $\overline{V}$.

$$\overline{V} = V\,\hat{i} = V\,\hat{i}_W$$

$$\frac{{}^{I}d\overline{V}}{dt} = \frac{{}^{C}d}{dt}(V\,\hat{i}_C) + \overline{\omega}^{CI}\ x\ V\,\hat{i}_C$$

$$= \frac{dV}{dt}\;\hat{i}_C + (-\dot{\chi}\,\sin\gamma\;\hat{i}_C + \omega\;\hat{k}_W)\ x\ V\,\hat{i}_C$$

$$= \frac{dV}{dt}\;\hat{i}_C + V\omega\;(\hat{k}_W\ x\ \hat{i}_C) \qquad \textit{but}\quad \hat{i}_C = \hat{i}_W$$

$$\frac{{}^{I}d\overline{V}}{dt} = \frac{dV}{dt}\;\hat{i}_C + V\omega\;\hat{j}_W \tag{20}$$

Taking the second inertial derivative of $\overline{V}$,

$$\frac{{}^{I}d}{dt}\left(\frac{{}^{I}d\overline{V}}{dt}\right) = \frac{{}^{C}d}{dt}\left(\frac{dV}{dt}\,\hat{i}_C\right) + \overline{\omega}^{CI}\, x\left(\frac{dV}{dt}\,\hat{i}_C\right)$$

$$+ \frac{{}^{W}d}{dt}\left(V\omega\,\hat{j}_W\right) + \hat{\omega}^{WI}\, x\left(V\omega\,\hat{j}_W\right)$$

$$= \frac{dV^2}{dt^2}\,\hat{i}_C + (-\dot{\chi}\sin\gamma\,\hat{i}_C + \omega\,\hat{k}_W)\, x\left(\frac{dV}{dt}\,\hat{i}_C\right)$$

$$+ \left[\frac{dV}{dt}\,\omega + V\,\frac{d\omega}{dt}\right]\hat{j}_W + \overline{\omega}^{WI}\, x\left(V\omega\,\hat{j}_W\right)$$

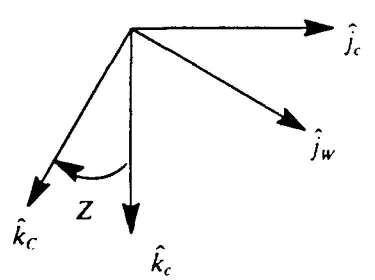
$$\frac{{}^{I}d^2\overline{V}}{dt^2} = \frac{d^2V}{dt^2}\,\hat{i}_C + \left[2\omega\frac{dV}{dt} + V\frac{d\omega}{dt}\right]\hat{j}_W + \overline{\omega}^{WI}\, x\left(V\omega\,\hat{j}_W\right) \quad \textbf{(21)}$$

Next determine $\overline{\omega}^{WI}$

$$\overline{\omega}^{WI} = \overline{\omega}^{WC} + \overline{\omega}^{CI}$$

$$\overline{\omega}^{WI} = \overline{\omega}^{WC} - \dot{\chi}\sin\gamma\,\hat{i}_C + \omega\,\hat{k}_W \quad \textbf{(22)}$$

where $\overline{\omega}^{WC}$ is defined by the following rotation



$$\overline{\omega}^{WC} = \dot{Z}\,\hat{i}_W$$

therefore with $\hat{i}_C = \hat{i}_W$

$$\frac{{}^I d^2\overline{V}}{dt^2} = \frac{d^2V}{dt^2}\,\hat{i}_W + \left[2\omega\,\frac{dV}{dt} + V\,\frac{d\omega}{dt}\right]\hat{j}_W$$
$$+\left[(\dot{Z} - \dot{\chi}\sin\gamma)\,\hat{i}_W + \omega\,\hat{k}_W\right] x\; V\omega\,\hat{j}_W$$

$$\frac{{}^I d^2\overline{V}}{dt^2} = \left(\frac{d^2V}{dt^2} - V\omega^2\right)\hat{i}_W + \left(2\omega\frac{dV}{dt} + V\frac{d\omega}{dt}\right)\hat{j}_W + \left[V\omega\;(Z - \chi\sin\gamma)\right]\hat{k}_W \quad \textbf{(23)}$$

Alternate Approach

The alternate approach taken to derive the Herbst's agility relationships was to take the first inertial derivative of Newton's 2nd Law of Motion as follows.

$$\frac{{}^{I}d\bar{F}}{dt} = \frac{{}^{I}d(m\bar{a})}{dt} \tag{24}$$

where

$$\bar{F} = (T\cos a - D - W_T \sin\gamma)\ \hat{i}_W + (W_T \cos\gamma \sin\phi)\ \hat{j}_W$$
$$- (L + T\sin a - W_T \cos\gamma\cos\phi)\ \hat{k}_W$$

$$\bar{a} = V\ \hat{i}_W + V(\psi\cos\gamma\cos\phi - \gamma\sin\phi)\ \hat{j}_W$$
$$- V(\gamma\cos\phi + \psi\cos\gamma\sin\phi)\ \hat{k}_W$$

$$\frac{{}^{I}d\bar{F}}{dt} = \frac{{}^{W}d\bar{F}}{dt} + \bar{\omega}^{WI}\ x\ \bar{F} \tag{25}$$

$$\frac{{}^{W}d\bar{F}}{dt} = \begin{bmatrix} T\cos a - T\dot{a}\sin a - D - W_T\sin\gamma - W_T\gamma\cos\gamma \\ W_T\cos\gamma\sin\phi - W_T\gamma\sin\gamma\sin\phi + W_T\phi\cos\gamma\cos\phi \\ -(L + T\sin a + Ta\cos a - W_T\cos\gamma\cos\phi + W_T\gamma\sin\gamma\cos\phi \\ \quad + W_T\phi\cos\gamma\sin\phi) \end{bmatrix}^{T} \begin{bmatrix} \hat{i}_W \\ \hat{j}_W \\ \hat{k}_W \end{bmatrix}$$

$$\omega^{WI}\ x\ \bar{F} = \begin{bmatrix} \hat{i}_W & \hat{j}_W & \hat{k}_W \\ (\phi - \psi\sin\gamma) & (\gamma\cos\phi + \psi\cos\gamma\sin\phi) & (\psi\cos\gamma\cos\phi - \gamma\sin\phi) \\ (T\cos a - D - W_T\sin\gamma) & (W_T\cos\gamma\sin\phi) & -(L + T\sin a \\ & & - W_T\cos\gamma\cos\phi) \end{bmatrix}$$

$$\bar{\omega}^{WI} \times \bar{F} = \begin{bmatrix} -(\gamma\cos\phi + \psi\cos\gamma\sin\phi)(L + T\sin a - W_T\cos\gamma\cos\phi) \\ \quad -(W_T\cos\gamma\sin\phi)(\psi\cos\gamma\cos\phi - \gamma\sin\phi) \\[2ex] (\phi - \psi\sin\gamma)(L + T\sin a - W_T\cos\gamma\cos\phi) \\ \quad + (T\cos a - D - W_T\sin\gamma)(\psi\cos\gamma\cos\phi - \gamma\sin\phi) \\[2ex] (\phi - \psi\sin\gamma)(W_T\cos\gamma\sin\phi) \\ \quad -(T\cos a - D - W_T\sin\gamma)(\gamma\cos\phi + \psi\cos\gamma\sin\phi) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \hat{i}_W \\[4ex] \hat{j}_W \\[4ex] \hat{k}_W \end{bmatrix}$$

$$\frac{{}^{I}d\bar{F}}{dt} = \begin{bmatrix} (T\cos a - T\dot{a}\sin a - D - W_T\sin\gamma - W_T\gamma\cos\gamma) - (L\gamma\cos\phi \\ + T\gamma\cos\phi\sin a - W_T\gamma\cos^2\phi\cos\gamma + L\psi\cos\gamma\sin\phi \\ + T\psi\cos\gamma\sin\phi\sin a - W_T\psi\cos^2\gamma\sin\phi\cos\phi) \\ -(W_T\psi\cos^2\gamma\sin\phi\cos\phi - W_T\gamma\cos\gamma\sin^2\phi) \\[2ex] (W_T\cos\gamma\sin\phi - W_T\gamma\sin\gamma\sin\phi + W_T\phi\cos\gamma\cos\phi) + (L\phi \\ + T\phi\sin a - W_T\phi\cos\gamma\cos\phi - L\psi\sin\gamma - T\psi\sin\gamma\sin a \\ + W_T\psi\sin\gamma\cos\gamma\cos\phi + (T\psi\cos a\cos\gamma\cos\phi - T\gamma\cos a\sin\phi \\ - D\psi\cos\gamma\cos\phi + D\gamma\sin\phi - W_T\psi\sin\gamma\cos\gamma\cos\phi \\ + W_T\gamma\sin\gamma\sin\phi) \\[2ex] (-L - T\sin a - Ta\cos a + W_T\cos\gamma\cos\phi - W_T\gamma\sin\gamma\cos\phi \\ - W_T\phi\cos\gamma\sin\phi) + (W_T\phi\cos\gamma\sin\phi - W_T\psi\sin\gamma\cos\gamma\sin\phi) \\ -(T\gamma\cos a\cos\phi + T\psi\cos a\cos\gamma\sin\phi - D\gamma\cos\phi - D\psi\cos\gamma\sin\phi \\ - W_T\gamma\sin\gamma\cos\phi - W_\psi\sin\gamma\cos\gamma\sin\phi) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \hat{i}_W \\[8ex] \hat{j}_W \\[8ex] \hat{k}_W \end{bmatrix}$$

$$\frac{{}^{I}d(m\bar{a})}{dt} = \left(\frac{dm}{dt}\right)\bar{a} + m\,\frac{{}^{I}d\bar{a}}{dt} \tag{26}$$

where

$$m = \frac{W_T}{g} \quad , \quad \frac{dm}{dt} = \frac{W_T}{g}$$

$$\left(\frac{dm}{dt}\right)\bar{a} = \left(\frac{W_T}{g}\right)\left[V\,\hat{i}_W + V(\psi\cos\gamma\cos\phi - \gamma\sin\phi)\,\hat{j}_W - V(\gamma\cos\phi + \psi\cos\gamma\sin\phi)\,\hat{k}_W\right]$$

$$m\,\frac{{}^{I}d\bar{a}}{dt} = \left(\frac{W_T}{g}\right)\begin{bmatrix} \dot{V} - V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 + (\psi\cos\gamma\cos\phi \\ \quad - \dot{\gamma}\sin\phi)^2] \\ 2\dot{V}(\psi\cos\gamma\cos\phi - \gamma\sin\phi) + V(\ddot{\psi}\cos\gamma\cos\phi \\ \quad - 2\psi\gamma\sin\gamma\cos\phi - \ddot{\gamma}\sin\phi - \psi^2\sin\gamma\cos\gamma\sin\phi) \\ -2\dot{V}(\psi\cos\gamma\sin\phi + \gamma\cos\phi) - V(\ddot{\psi}\cos\gamma\sin\phi \\ \quad - 2\psi\gamma\sin\gamma\sin\phi + \gamma\cos\phi + \psi^2\sin\gamma\cos\gamma\cos\phi) \end{bmatrix}^T \begin{bmatrix} \hat{i}_W \\ \hat{j}_W \\ \hat{k}_W \end{bmatrix}$$

$$\frac{{}^{I}d(m\bar{a})}{dt} = \left(\frac{1}{g}\right)\begin{bmatrix} W_T V + W_T V - W_T V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 \\ \quad + (\psi\cos\gamma\cos\phi - \gamma\sin\phi)^2)] \\ (W_T V + 2W_T V)(\psi\cos\gamma\cos\phi - \gamma\sin\phi) \\ \quad + W_T V(\psi\cos\gamma\cos\phi - 2\psi\gamma\sin\gamma\cos\phi - \gamma\sin\phi \\ \quad - \psi^2\sin\gamma\cos\gamma\sin\phi) \\ -(W_T V + 2W_T V)(\psi\cos\gamma\sin\phi + \gamma\cos\phi) \\ \quad - W_T V(\psi\cos\gamma\sin\phi - 2\psi\gamma\sin\gamma\sin\phi + \gamma\cos\phi \\ \quad + \psi^2\sin\gamma\cos\gamma\cos\phi) \end{bmatrix}^T \begin{bmatrix} \hat{i}_W \\ \hat{j}_W \\ \hat{k}_W \end{bmatrix}$$

Now equating the components of the left and right hand sides of equation 26

$$\frac{{}^{I}dF}{dt} = \frac{{}^{I}d(m\bar{a})}{dt}$$

$$\left[\hat{i}_W\right]$$

$$T\cos a - Ta - Ta\sin a - D - W_T\sin\gamma - W_T\gamma\cos\gamma - L\gamma\cos\phi - T\gamma\cos\phi\sin a$$
$$+ W_T\gamma\cos\gamma(\cos^2\phi + \sin^2\phi) - L\psi\cos\gamma\sin\phi - T\psi\cos\gamma\sin\phi\sin a =$$
$$\left(\frac{1}{g}\right)\left[W_T V + W_T V - W_T V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 + (\psi\cos\gamma\cos\phi - \gamma\sin\phi)^2]\right]$$

$$T\cos\alpha - T\sin\alpha(\alpha + \gamma\cos\phi + \psi\cos\gamma\sin\phi) - D - W_T\sin\gamma$$
$$- L(\dot{\gamma}\cos\phi + \psi\cos\gamma\sin\phi) =$$
$$(\frac{1}{g})\left[W_T V + W_T(V - V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 + (\psi\cos\gamma\cos\phi - \gamma\sin\phi)^2]\right]$$

$$\left[(\dot{T}\cos\alpha - T\dot{\alpha}\sin\alpha) - D\right] - (T\sin\alpha + L)(\gamma\cos\phi + \psi\cos\gamma\sin\phi) =$$
$$W_T(\sin\gamma\frac{\dot{V}}{g} + \frac{W_T}{g}\left[V - V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 + (\psi\cos\gamma\cos\phi - \gamma\sin\phi)^2]\right]$$

solve for $\dot{V}$

$$\boxed{\begin{aligned}\dot{V} = (\frac{g}{W_T})[(T\cos\alpha - T\alpha\sin\alpha - D) - (T\sin\alpha + L)(\gamma\cos\phi + \psi\cos\gamma\sin\phi)\\ - W_T(\sin\gamma + \frac{V}{g})] + V[(\gamma\cos\phi + \psi\cos\gamma\sin\phi)^2 + (\psi\cos\gamma\cos\phi - \gamma\sin\phi)^2]\end{aligned}} \quad \textbf{(27)}$$

$$\left[\hat{j}_W\right]$$

$$W_T\cos\gamma\sin\phi + (T\sin\alpha + L)(\dot{\phi} - \psi\sin\gamma) + (T\cos\alpha - D)(\psi\cos\gamma\cos\phi - \gamma\sin\phi) =$$
$$(\frac{1}{g})[W_T V(\psi\cos\gamma\cos\phi - \gamma\sin\phi) + W_T[2V(\psi\cos\gamma\cos\phi - \gamma\sin\phi)$$
$$+ V(\psi\cos\gamma\cos\phi - 2\psi\gamma\sin\gamma\cos\phi - \gamma\sin\phi - \psi^2\sin\gamma\cos\gamma\sin\phi)]]$$

$$\left[\hat{k}_W\right]$$

$$W_T\cos\gamma\cos\phi - L - T\sin\alpha - T\alpha\cos\alpha - (T\cos\alpha - D)(\gamma\cos\phi + \psi\cos\gamma\sin\phi) =$$
$$(\frac{1}{g})[-(W_T V + 2W_T V)(\psi\cos\gamma\sin\phi + \gamma\cos\phi) - W_T V(\psi\cos\gamma\sin\phi - 2\psi\gamma\sin\gamma\sin\phi$$
$$+ \gamma\cos\phi + \psi^2\sin\gamma\cos\gamma\cos\phi)]$$

multiply the j component by cos Φ and the k component by sin Φ and then add

$$\left[\cos\phi[\hat{j}_W] + \sin\phi[\hat{k}_W]\right]$$

$$[(T\sin a + L)(\phi - \psi\sin\gamma)\cos\phi + (T\cos a - D)(\psi\cos\gamma\cos^2\phi)$$
$$- (T\cos a - D)(\gamma\sin\phi\cos\phi)] + [(L + \dot{T}\sin a + T\dot{a}\cos a)\sin\phi$$
$$+ (T\cos a - D)(\psi\cos\gamma\sin^2\phi) + (T\cos a - D)(\gamma\cos\phi\sin\phi)] =$$

$$[W_T[(\frac{V}{g})(\psi\cos\gamma\cos^2\phi - \gamma\sin\phi\cos\phi) - cos\gamma\sin\phi\cos\phi]$$
$$+ (\frac{W_T}{g})[2V(\psi\cos\gamma\cos^2\phi - \gamma\sin\phi\cos\phi) + V(\psi\cos\gamma\cos^2\phi - 2\psi\gamma\sin\gamma\cos^2\phi$$
$$- \gamma\sin\phi\cos\phi - \psi^2\sin\gamma\cos\gamma\sin\phi\cos\phi)]] + [W_T[(\frac{V}{g})(\psi\cos\gamma\sin^2\phi$$
$$+ \gamma\cos\phi\sin\phi) + \cos\gamma\cos\phi\sin\phi] + (\frac{W}{g})[2V(\psi\cos\gamma\sin^2\phi + \gamma\cos\phi\sin\phi)$$
$$+ V[\psi\cos\gamma\sin^2\phi - 2\psi\gamma\sin\gamma\sin^2\phi + \gamma\cos\phi\sin\phi + \psi^2\sin\gamma\cos\gamma\cos\phi\sin\phi]]]$$

$$(T\sin a + L)(\phi - \psi\sin\gamma)\cos\phi + (T\cos a - D)(\psi\cos\gamma)$$
$$+ (LT\sin a + T\dot{a}\cos a)\sin\phi =$$
$$W_T(\frac{V}{g})(\psi\cos\gamma) + (\frac{W_T}{g})[(2V\psi\cos\gamma) + V(\psi\cos\gamma - 2\psi\gamma\sin\gamma)]$$

solve for $\ddot{\psi}$

$$\boxed{\begin{aligned}\psi &= (\frac{1}{V\cos\gamma})[(\frac{g}{W_T})[(T\sin a + L)(\phi - \psi\sin\gamma)\cos\phi + (T\cos a - D)(\psi\cos\gamma) \\ &+ (L + T\sin a + T\dot{a}\cos a)\sin\phi - W_T(\frac{V}{g})\psi\cos\gamma] - 2V\psi\cos\gamma + 2V\psi\gamma\sin\gamma]\end{aligned}} \quad \textbf{(28)}$$

multiply the j component by sin Φ and the k component by − cos Φ and then add

$$\left[\sin\phi[\hat{j}_W] - \cos\phi[\hat{k}_W]\right]$$

$$\begin{aligned}
&[(T\sin\alpha + L)(\dot\phi - \dot\psi\sin\gamma)\sin\phi + (T\cos\alpha - D)(\dot\psi\cos\gamma\cos\phi\sin\phi) \\
&\quad - (T\cos\alpha - D)(\dot\gamma\sin^2\phi)] - [(L + \dot T\sin\alpha + T\dot\alpha\cos\alpha)\cos\phi \\
&\quad + (T\cos\alpha - D)(\dot\gamma\cos^2\phi) + (T\cos\alpha - D)(\dot\psi\cos\gamma\sin\phi\cos\phi)] = \\
&[W_T[(\frac{\dot V}{g})(\dot\psi\cos\gamma\cos\phi\sin\phi - \dot\gamma\sin^2\phi) - \cos\gamma\sin^2\phi] + (\frac{W_T}{g})[2\dot V(\dot\psi\cos\gamma\sin\phi\cos\phi \\
&\quad + \dot\gamma\cos^2\phi) + V(\ddot\psi\cos\gamma\sin\phi\cos\phi - 2\dot\psi\dot\gamma\sin\gamma\sin\phi\cos\phi \\
&\quad + \ddot\gamma\cos^2\phi + \dot\psi^2\sin\gamma\cos\gamma\cos^2\phi)]]
\end{aligned}$$

$$\begin{aligned}
&(T\sin\alpha + L)(\dot\phi - \dot\psi\sin\gamma)\sin\phi - (L + \dot T\sin\alpha + T\dot\alpha\cos\alpha)\cos\phi - (T\cos\alpha - D)\dot\gamma = \\
&\quad - W_T[(\frac{\dot V}{g})\dot\gamma + \cos\gamma] + (\frac{W_T}{g})[-2\dot V\dot\gamma - V(\ddot\gamma + \dot\psi^2\sin\gamma\cos\gamma)]
\end{aligned}$$

solve for $\ddot\gamma$

$$\boxed{\begin{aligned}
\ddot\gamma = (\frac{1}{V})[(\frac{-g}{W_T})[&(T\sin\alpha + L)(\dot\phi - \dot\psi\sin\gamma)\sin\phi - (L + \dot T\sin\alpha + T\dot\alpha\cos\alpha)\cos\phi \\
&- (T\cos\alpha - D)\dot\gamma + W_T(\frac{\dot V\dot\gamma}{g} + \cos\gamma)] - 2\dot V\dot\gamma - V\dot\psi^2\sin\gamma\cos\gamma]
\end{aligned}} \quad \textbf{(29)}$$

Appendix B: Results From Parametric Analyses

Table 7

Herbst Agility Metrics
(ALT = 10000 ft, M = 0.2728)

Agility Metric	ΔT/W - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Turn (deg/sec^2)	-.7309	-.8109	-.8906	-.9700	-1.0492
Axial (ft/sec^3)	1.7164	1.8440	1.9628	2.0733	2.1768
Pitch (deg/sec^2)	-.3936	-.4367	-.4802	-.5225	-.5652
Agility Metric	**ΔT/W - % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Turn (deg/sec^2)	-.6830	-7.846	-.8906	-1.0008	-1.1169
Axial (ft/sec^3)	1.5886	1.7709	1.9628	2.1628	2.3734
Pitch (deg/sec^2)	-.3357	-.4058	-.4802	-.5593	-.6451
Agility Metric	**ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	-.9383	-.9169	-.8906	-.8598	-.8257
Axial (ft/sec^3)	2.1173	2.0420	1.9628	1.8801	1.7976
Pitch (deg/sec^2)	-.5452	-.5133	-.4802	-.4456	-.4097
Agility Metric	**ΔW/S - % S = 300 ft^2 (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	-1.1434	-1.0070	-.8906	-.7894	-.7008
Axial (ft/sec^3)	2.4215	2.1736	1.9628	1.7798	1.6206
Pitch (deg/sec^2)	-.6645	-.5637	-.4802	-.4091	-.3477

Table 8

Herbst Agility Metrics
(ALT = 10000 ft, M = 0.4)

Agility Metric	ΔT/W – % WT = 20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Turn (deg/sec^2)	.1120	0130	–.0856	–.1840	–.2821
Axial (ft/sec^3)	–.4764	–.0560	.3488	.7384	1.1136
Pitch (deg/sec^2)	.0863	.0102	–.0658	–.1415	–.2171
Agility Metric	**ΔT/W – % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Turn (deg/sec^2)	–.0685	–.0771	–.0856	–.0946	–.1037
Axial (ft/sec^3)	.2814	.3166	.3488	.3835	.4190
Pitch (deg/sec^2)	–.0507	–.0580	–.0658	–.0739	–.0820
Agility Metric	**ΔW/S – % WT = 20000 lbs (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	.1394	.0146	–.0856	–.1664	–.2313
Axial (ft/sec^3)	–.5908	–.0635	.3488	.6708	.9205
Pitch (deg/sec^2)	.1102	.0113	–.0658	–.1259	–.1730
Agility Metric	**ΔW/S – % S = 300 ft^2 (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	–.1061	–.0951	–.0856	–.0774	–.0701
Axial (ft/sec^3)	.4282	.3850	.3488	.3173	.2882
Pitch (deg/sec^2)	–.0841	–.0744	–.0658	–.0583	–.0522

Table 9

Herbst Agility Metrics
(ALT = 10000 ft, M = 0.8)

Agility Metric	$\Delta T/W$ – % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Turn (deg/sec^2)	1.034	0.970	0.906	0.842	0.778
Axial (ft/sec^3)	-6.798	-6.350	-5.906	-5.467	-5.031
Pitch (deg/sec^2)	.9354	.8776	.8202	.7620	.7043
Agility Metric	**$\Delta T/W$ – % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Turn (deg/sec^2)	1.219	1.064	0.906	0.769	0.636
Axial (ft/sec^3)	-8.934	-7.367	-5.906	-4.760	-3.739
Pitch (deg/sec^2)	1.1003	.9558	.8202	.6893	.5717
Agility Metric	**$\Delta W/S$ – % WT=20000 lbs (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	0.747	0.829	0.906	0.995	1.073
Axial (ft/sec^3)	-4.369	-5.136	-5.906	-6.842	-7.713
Pitch (deg/sec^2)	.6714	.7433	.8202	.8934	.9673
Agility Metric	**$\Delta W/S$ – % S = 300 ft^2 (Baseline W/S = 66.7 lbs/ft^2)**				
Turn (deg/sec^2)	0.607	0.762	0.906	1.057	1.191
Axial (ft/sec^3)	-3.525	-4.703	-5.906	-7.296	-8.640
Pitch (deg/sec^2)	.5452	.6831	.8202	.9489	1.0742

Table 10

Eidetics Agility Metrics
(ALT = 10000 ft, M = 0.2728)

Agility Metric	ΔT/W - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
Agility Metric	-10	-5	0	5	10
Torsional (deg/sec^2)	2.484	2.484	2.484	2.484	2.484
Axial (ft/sec^2)	173.126	181.939	190.716	199.458	208.167
Agility Metric	ΔT/W - % Thrust = const (Baseline T/W = 1.66 @ sea level)				
Torsional (deg/sec^2)	2.159	2.325	2.484	2.635	2.780
Axial (ft/sec^2)	171.645	181.177	190.716	200.243	209.787
Agility Metric	ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
Torsional (deg/sec^2)	2.812	2.643	2.484	2.333	2.190
Axial (ft/sec^2)	192.387	191.541	190.716	189.949	189.266
Agility Metric	ΔW/S - % S= 300 ft^2 (Baseline W/S = 66.7 ft^2)				
Torsional (deg/sec^2)	2.812	2.643	2.484	2.333	2.190
Axial (ft/sec^2)	211.934	200.781	190.716	181.623	173.399

Table 11

Eidetics Agility Metrics
(ALT = 10000 ft, M = 0.4)

Agility Metric	$\underline{\Delta T/W - \%}$ WT = 20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Torsional (deg/sec^2)	3.530	3.530	3.530	3.530	3.530
Axial (ft/sec^2)	266.550	279.941	293.292	306.604	319.877
Agility Metric	$\underline{\Delta T/W - \%}$ Thrust = const (Baseline T/W = 1.66 @ sea level)				
Torsional (deg/sec^2)	3.262	3.399	3.530	3.656	3.778
Axial (ft/sec^2)	263.953	278.658	293.292	307.975	322.635
Agility Metric	$\underline{\Delta W/S - \%}$ WT = 20000 lbs (Baseline W/S = 66.7 ft^2)				
Torsional (deg/sec^2)	3.804	3.663	3.530	3.405	3.287
Axial (ft/sec^2)	296.173	294.693	293.292	292.034	290.817
Agility Metric	$\underline{\Delta W/S - \%}$ S = 300 ft^2 (Baseline W/S = 66.7 ft^2)				
Torsional (deg/sec^2)	3.804	3.663	3.530	3.405	3.287
Axial (ft/sec^2)	325.888	308.748	293.292	279.355	266.648

Table 12

Eidetics Agility Metrics
(ALT = 10000 ft, M = 0.8)

Agility Metric	$\Delta T/W$ - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	-5	0	5	10
Torsional (Inst. deg/sec^2)	3.165	3.165	3.165	3.165	3.165
Torsional (Sust. deg/sec^2)	2.641	2.687	2.730	2.770	2.809
Axial (ft/sec^2)	557.639	581.536	605.419	629.289	653.147
Agility Metric	**$\Delta T/W$ - % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Torsional (Inst. deg/sec^2)	3.165	3.165	3.165	3.165	3.165
Torsional (Sust. deg/sec^2)	2.584	2.659	2.730	2.797	2.861
Axial (ft/sec^2)	554.396	579.374	605.419	631.261	656.888
Agility Metric	**$\Delta W/S$ - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
Torsional (Inst. deg/sec^2)	3.165	3.165	3.165	3.165	3.165
Torsional (Sust. deg/sec^2)	2.786	2.757	2.730	2.703	2.678
Axial (ft/sec^2)	610.542	607.712	605.419	603.530	603.166
Agility Metric	**$\Delta W/S$ - % S= 300 ft^2 (Baseline W/S = 66.7 ft^2)**				
Torsional (Inst. deg/sec^2)	3.165	3.165	3.165	3.165	3.165
Torsional (Sust. deg/sec^2)	2.874	2.800	2.730	2.662	2.598
Axial (ft/sec^2)	662.710	632.633	605.419	580.597	558.970

Table 13

Comparison of Classic Turn Rate (TR) and Eidetics Turn Agility (TA) Metric
(ALT = 10000 ft)

Metric	<u>ΔT/W - %</u> WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
TR/M_{corner} (deg/sec)	26.65/.6395	26.65/.6395	26.65/.6395	26.65/.6395	26.65/.6395
TA/M_{corner} (deg/sec^2)	3.890/.6395	3.890/.6395	3.890/.6395	3.890/.6395	3.890/.6395
TA_{max}/M_{max} (deg/sec^2)	3.901/.5958	3.901/.5958	3.901/.5958	3.901/.5958	3.901/.5958
Metric	<u>ΔT/W - %</u> Thrust = const (Baseline T/W = 1.66 @ sea level)				
TR/M_{corner} (deg/sec)	25.29/.6741	25.98/.6562	26.65/.6395	27.31/.6241	27.96/.6098
TA/M_{corner} (deg/sec^2)	3.703/.6741	3.798/.6562	3.890/.6395	3.979/.6241	4.067/.6098
TA_{max}/M_{max} (deg/sec^2)	3.714/.6280	3.808/.6113	3.901/.5958	3.991/.5814	4.078/.5681
Metric	<u>ΔW/S - %</u> WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
TR/M_{corner} (deg/sec)	28.10/.6067	27.35/.6233	26.65/.6395	26.01/.6553	25.41/.6708
TA/M_{corner} (deg/sec^2)	4.086/.6067	3.984/.6233	3.890/.6395	3.802/.6553	3.721/.6708
TA_{max}/M_{max} (deg/sec^2)	4.098/.5652	3.995/.5807	3.901/.5958	3.813/.6105	3.731/.6249
Metric	<u>ΔW/S - %</u> S= 300 ft^2 (Baseline W/S = 66.7 ft^2)				
TR/M_{corner} (deg/sec)	28.10/.6067	27.35/.6233	26.65/.6395	26.01/.6553	25.41/.6708
TA/M_{corner} (deg/sec^2)	4.086/.6067	3.984/.6233	3.890/.6395	3.802/.6553	3.721/.6708
TA_{max}/M_{max} (deg/sec^2)	4.098/.5652	3.995/.5807	3.901/.5958	3.813/.6105	3.731/.6249

Table 14

Kalviste's Performance Metrics
(ALT = 10000 ft, M 0.2728)

Metric	ΔT/W – % WT = 20000 lbs (Baseline T/W = 1.66 @ sea level)				
Metric	**-10**	**-5**	**0**	**5**	**10**
DT (ft-sec)	29756	28748	28001	27075	26393
V/Vc	.3246/.6395 .5076	.3335/.6395 .5215	.3423/.6395 .5353	.3506/.6395 .5482	.3590/.6395 .5614
CCT (sec)	12.0	11.7	11.5	11.2	11.0
Metric	**ΔT/W – % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
DT (ft-sec)	35392	31228	28001	25143	22592
V/Vc	.3408/.6741 .5056	.3414/.6562 .5203	.3423/.6395 .5353	.3430/.6241 .5496	.3436/.6098 .5635
CCT (sec)	12.9	12.1	11.5	10.9	10.3
Metric	**ΔW/S – % WT = 20000 lbs (Baseline W/S = 66.7 ft^2)**				
DT (ft-sec)	23573	25744	28001	30121	32305
V/Vc	.3261/.6067 .5375	.3343/.6233 .5363	.3423/.6395 .5353	.3499/.6553 .5340	.3574/.6708 .5328
CCT (sec)	10.7	11.1	11.5	11.8	12.1
Metric	**ΔW/S – % S = 300 ft^2 (Baseline W/S = 66.7 ft^2)**				
DT (ft-sec)	22127	24862	28001	31131	34359
V/Vc	.3437/.6067 .5665	.3429/.6233 .5501	.3423/.6395 .5353	.3415/.6553 .5211	.3408/.6708 .5081
CCT (sec)	10.2	10.8	11.5	12.1	12.7

Table 15

Kalviste's Performance Metrics
(ALT = 10000 ft, M = 0.4)

Metric	$\Delta T/W$ - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
DT (ft–sec)	27060	26369	25701	25055	24428
V/Vc	.3402/.6395 .5320	.3490/.6395 .5457	.3576/.6395 .5592	.3660/.6395 .5723	.3743/.6395 .5853
CCT (sec)	12.4	11.9	11.3	10.9	10.4
Metric	$\Delta T/W$ - % Thrust = const (Baseline T/W = 1.66 @ sea level)				
DT (ft–sec)	32172	28740	25701	23204	20963
V/Vc	.3558/.6741 .5278	.3567/.6562 .5436	.3576/.6395 .5592	.3584/.6241 .5743	.3594/.6098 .5894
CCT (sec)	12.7	12.0	11.3	10.8	10.2
Metric	$\Delta W/S$ - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
DT (ft–sec)	21666	23751	25701	27718	30050
V/Vc	.3419/.6067 .5635	.3498/.6233 .5612	.3576/.6395 .5592	.3652/.6553 .5573	.3725/.6708 .5553
CCT (sec)	11.1	11.2	11.3	11.4	11.6
Metric	$\Delta W/S$ - % S= 300 ft^2 (Baseline W/S = 66.7 ft^2)				
DT (ft–sec)	20717	23135	25701	28416	31538
V/Vc	.3596/.6067 .5927	.3584/.6233 .5750	.3576/.6395 .5592	.3568/.6553 .5445	.3559/.6708 .5306
CCT (sec)	10.2	10.8	11.3	11.9	12.6

Table 16

Kalviste's Performance Metrics
(ALT = 10000 ft, M = 0.8)

Metric	$\underline{\Delta T/W - \%}$ WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
DT (ft–sec)	24314	24222	24438	24439	24765
V/Vc	.4344/.6395 .6793	.4467/.6395 .6985	.4570/.6395 .7146	.4705/.6395 .7357	.4825/.6395 .7545
CCT (sec)	18.9	17.8	17.0	16.1	15.4
Metric	$\underline{\Delta T/W - \%}$ **Thrust = const (Baseline T/W = 1.66 @ sea level)**				
DT (ft–sec)	26899	25137	24438	24290	25028
V/Vc	.4346/.6741 .6447	.4452/.6562 .6785	.4570/.6395 .7146	.4766/.6241 .7637	.5072/.6098 .8317
CCT (sec)	19.4	18.0	17.0	15.8	14.6
Metric	$\underline{\Delta W/S - \%}$ **WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
DT (ft–sec)	23958	23908	24438	25240	26267
V/Vc	.4740/.6067 .7813	.4637/.6233 .7439	.4570/.6395 .7146	.4545/.6553 .6936	.4546/.6708 .6777
CCT (sec)	16.3	16.7	17.0	17.2	17.4
Metric	$\underline{\Delta W/S - \%}$ **S= 300 ft^2 (Baseline W/S = 66.7 ft^2)**				
DT (ft–sec)	25344	24325	24438	25117	26463
V/Vc	.5161/.6067 .8507	.4776/.6233 .7662	.4570/.6395 .7146	.4455/.6553 .6798	.4367/.6708 .6510
CCT (sec)	14.3	15.8	17.0	18.0	19.1

Table 17

Dorn's Large Amplitude Task Agility
(ALT = 10000 ft, M = 0.2728)

Metric	1/DT Parameter - $x10^{-5}(ft\text{-}sec)^{-1}$				
	-10	**-5**	**0**	**5**	**10**
T/W WT=20000 lbs	3.361	3.479	3.571	3.693	3.789
T/W Thrust=const	2.825	3.202	3.571	3.977	4.426
W/S WT=20000 lbs	4.242	3.884	3.571	3.320	3.095
W/S S=300 ft	4.519	4.022	3.571	3.212	2.910
Metric	**Energy Agility - (ft-sec)**				
T/W WT=20000 lbs	-3901.8	-4508.0	-5134.4	-5652.8	-6209.4
T/W Thrust=const	-5781.6	-5397.2	-5134.4	-4857.2	-4568.1
W/S WT=20000 lbs	-3467.7	-4276.8	-5134.4	-5963.1	-6822.6
W/S S=300 ft	-4525.1	-4795.4	-5134.4	-5405.0	-5675.6
Metric	**Large Amplitude Task Agility - $A_{L.A.T.}$ $x10^{-9}(ft\text{-}sec)^{-2}$**				
T/W WT=20000 lbs	-8.614	-7.717	-6.955	-6.533	-6.102
T/W Thrust=const	-4.886	-5.933	-6.955	-8.188	-9.689
W/S WT=20000 lbs	-12.233	-9.082	-6.955	-5.568	-4.536
W/S S=300 ft	-9.987	-8.387	-6.955	-5.943	-5.127

Table 18

Dorn's Large Amplitude Task Agility
(ALT = 10000 ft, M = 0.4)

Metric	1/DT Parameter – x10^{-5}(ft–sec)$^{-1}$				
	-10	**-5**	**0**	**5**	**10**
T/W WT=20000 lbs	3.695	3.792	3.891	3.991	4.094
T/W Thrust=const	3.108	3.479	3.891	4.310	4.770
W/S WT=20000 lbs	4.616	4.210	3.891	3.608	3.328
W/S S=300 ft	4.827	4.322	3.891	3.519	3.171
Metric	**Energy Agility – (ft–sec)**				
T/W WT=20000 lbs	7144.1	6067.4	5079.1	4169.1	3328.9
T/W Thrust=const	5730.6	5409.5	5079.1	4811.8	4535.7
W/S WT=20000 lbs	6343.3	5759.6	5079.1	4391.0	3743.0
W/S S=300 ft	4550.5	4816.0	5079.1	5343.5	5679.7
Metric	**Large Amplitude Task Agility – $A_{L.A.T.}$ x10^{-9}(ft–sec)$^{-2}$**				
T/W WT=20000 lbs	5.172	6.250	7.661	9.573	12.298
T/W Thrust=const	5.424	6.431	7.661	8.957	10.517
W/S WT=20000 lbs	7.277	7.310	7.661	8.217	8.891
W/S S=300 ft	10.608	8.974	7.661	6.586	5.583

Table 19

Dorn's Large Amplitude Task Agility
(ALT = 10000 ft, M = 0.8)

Metric	1/DT Parameter - $x10^{-5}(ft\text{-}sec)^{-1}$				
	-10	-5	0	5	10
T/W WT = 20000 lbs	4.113	4.128	4.092	4.092	4.038
T/W Thrust = const	3.718	3.978	4.092	4.117	3.996
W/S WT = 20000 lbs	4.174	4.183	4.092	3.962	3.807
W/S S = 300 ft	3.946	4.111	4.092	3.981	3.779
Metric	**Energy Agility - (ft-sec)**				
T/W WT = 20000 lbs	88795	80976	75056	68159	62747
T/W Thrust = const	94204	83900	75056	64605	53022
W/S WT = 20000 lbs	65772	70607	75056	78248	80573
W/S S = 300 ft	50310	64149	75056	83634	92057
Metric	**Large Amplitude Task Agility - $A_{L.A.T.}$ $x10^{-10}(ft\text{-}sec)^{-2}$**				
T/W WT = 20000 lbs	4.632	5.098	5.452	6.003	6.435
T/W Thrust = const	3.947	4.741	5.452	6.373	7.536
W/S WT = 20000 lbs	6.346	5.924	5.452	5.063	4.725
W/S S = 300 ft	7.843	6.409	5.452	4.760	4.105

Table 20

McAtee's Metrics
(ALT = 10000 ft, M = 0.2728)

Metric	ΔT/W - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	-5	0	5	10
Turn Rate (deg/sec)	9.546	9.546	9.546	9.546	9.546
Bleed Rate max g (Kcas/sec)	11.56	12.83	14.09	15.35	16.60
Acceleration 1g (Kcas/sec)	17.27	18.43	19.59	20.76	21.91
Metric	**ΔT/W - % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Turn Rate (deg/sec)	8.139	8.851	9.546	10.221	10.886
Bleed Rate max g (Kcas/sec)	12.68	13.38	14.09	14.79	15.50
Acceleration 1g (Kcas/sec)	17.13	18.37	19.59	20.81	21.91
Metric	**ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
Turn Rate (deg/sec)	11.035	10.260	9.546	8.883	8.272
Bleed Rate max g (Kcas/sec)	12.84	13.50	14.09	14.61	15.08
Acceleration 1g (Kcas/sec)	19.71	19.65	19.59	19.54	19.48
Metric	**ΔW/S - % S = 300 ft^2 (Baseline W/S = 66.7 ft^2)**				
Turn Rate (deg/sec)	11.035	10.260	9.546	8.883	8.272
Bleed Rate max g (Kcas/sec)	15.65	14.83	14.09	13.42	12.80
Acceleration 1g (Kcas/sec)	22.28	20.87	19.59	18.43	17.35

Table 21

McAtee's Metrics
(ALT = 10000 ft, M = 0.4)

Metric	$\Delta T/W$ - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Turn Rate (deg/sec)	16.20	16.20	16.20	16.20	16.20
Bleed Rate max g (Kcas/sec)	-1.550	-.1813	1.186	2.549	3.909
Acceleration 1g (Kcas/sec)	18.57	19.74	20.91	22.08	23.25
Metric	**$\Delta T/W$ - % Thrust = const (Baseline T/W = 1.66 @ sea level)**				
Turn Rate (deg/sec)	14.46	15.33	16.20	17.06	17.93
Bleed Rate max g (Kcas/sec)	1.069	1.122	1.186	1.243	1.304
Acceleration 1g (Kcas/sec)	18.53	19.72	20.91	22.09	23.26
Metric	**$\Delta W/S$ - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
Turn Rate (deg/sec)	18.12	17.11	16.20	15.37	14.62
Bleed Rate max g (Kcas/sec)	-1.724	-.1927	1.186	2.423	3.550
Acceleration 1g (Kcas/sec)	20.93	20.92	20.91	20.90	20.88
Metric	**$\Delta W/S$ - % S= 300 ft^2 (Baseline W/S = 66.7 ft^2)**				
Turn Rate (deg/sec)	18.12	17.11	16.20	15.37	14.62
Bleed Rate max g (Kcas/sec)	1.319	1.246	1.186	1.125	1.075
Acceleration 1g (Kcas/sec)	23.52	22.15	20.91	19.78	18.75

Table 22

McAtee's Metrics
(ALT = 10000 ft, M = 0.8)

Metric	ΔT/W - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	-5	0	5	10
Turn Rate (deg/sec)	21.325	21.325	21.325	21.325	21.325
Bleed Rate 10g (Kcas/sec)	-22.68	-21.28	-19.87	-18.47	-17.07
Acceleration 1g (Kcas/sec)	19.13	20.41	21.69	22.97	24.24
Metric	ΔT/W - % Thrust = const (Baseline T/W = 1.66 @ sea level)				
Turn Rate (deg/sec)	21.326	21.308	21.325	21.326	21.312
Bleed Rate 10g (Kcas/sec)	-26.76	-23.20	-19.87	-16.77	-13.84
Acceleration 1g (Kcas/sec)	19.43	20.56	21.69	22.81	23.94
Metric	ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
Turn Rate (deg/sec)	21.310	21.325	21.325	21.309	21.324
Bleed Rate 10g (Kcas/sec)	-16.28	-18.07	-19.87	-21.68	-23.50
Acceleration 1g (Kcas/sec)	21.35	21.53	21.69	21.83	21.96
Metric	ΔW/S - % S= 300 ft^2 (Baseline W/S = 66.7 ft^2)				
Turn Rate (deg/sec)	21.310	21.325	21.325	21.309	21.324
Bleed Rate 10g (Kcas/sec)	-13.21	-16.61	-19.87	-23.03	-26.09
Acceleration 1g (Kcas/sec)	24.19	22.87	21.69	20.61	19.64

Table 23

Trajectory Results - Traj #1 - Vertical Loop
(ALT = 10000 ft, M = 0.8)

Metric	ΔT/W - % WT=20000 lbs (Baseline T/W = 1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Down Range Distance (ft)	1439.7	1424.5	1402.6	1424.0	1439.4
M_{final}	.4110	.4202	.4240	.4377	.4459
$Time_{mid}$ (sec)	8.3	8.2	8.1	8.1	8.0
$Altitude_{mid}$ (ft)	12909	12924	12940	12959	12979
Ratio of Mid to Initial Energy	.7039	.7106	.7174	.7244	.7317
Metric	**ΔT/W - % Thrust = const (Baseline T/W= 1.66 @ sea level)**				
Down Range Distance(ft)	1462.0	1426.5	1402.6	1439.2	1486.8
M_{final}	.4297	.4292	.4240	.4291	.4288
$Time_{mid}$ (sec)	8.9	8.5	8.1	7.8	7.6
$Altitude_{mid}$ (ft)	13075	12992	12940	12918	12926
Ratio of Mid to Initial Energy	.7113	.7133	.7174	.7234	.7314
Metric	**ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
Down Range Distance(ft)	1470.6	1435.7	1402.6	1422.5	1450.5
M_{final}	.4101	.4199	.4240	.4374	.4509
$Time_{mid}$ (sec)	7.7	7.9	8.1	8.4	8.6
$Altitude_{mid}$ (ft)	12861	12893	12940	13001	13073
Ratio of Mid to Initial Energy	.7157	.7159	.7174	.7196	.7233

Metric	$\underline{\Delta W/S - \%}$ WT = 20000 lbs (Baseline W/S = 66.7 ft²)				
	-10	**-5**	**0**	**5**	**10**
Down Range Distance(ft)	1507.6	1456.5	1402.6	1445.3	1496.2
M_{final}	.4283	.4283	.4240	.4284	.4331
$Time_{mid}$ (sec)	7.6	7.8	8.1	8.5	8.8
$Altitude_{mid}$ (ft)	12931	12918	12940	12989	13058
Ratio of Mid to Initial Energy	.7339	.7237	.7174	.7135	.7115

Table 24

Trajectory Results - Traj #2 - Scissors Maneuver
(ALT = 10000 ft, M = 0.4)

Metric	ΔT/W - % WT=20000 lbs (Baseline T/W=1.66 @ sea level)				
	-10	**-5**	**0**	**5**	**10**
Radial Distance (ft)	3635	3610	3610	3580	3577
M_{final}	.3263	.3318	.3374	.3430	.3486
$Time_{final}$ (sec)	10.7	10.4	10.4	10.1	10.1
$Altitude_{final}$ (ft)	10115	10174	10224	10275	10323
Ratio of Final to Initial Energy	.9338	.9434	.9525	.9618	.9708
Metric	**ΔT/W - % Thrust=const (Baseline T/W=1.66 @ sea level)**				
Radial Distance (ft)	3856	3733	3610	3489	3348
M_{final}	.3461	.3415	.3374	.3335	.3302
$Time_{final}$ (sec)	10.8	10.6	10.4	10.2	9.9
$Altitude_{final}$ (ft)	10037	10134	10224	10308	10380
Ratio of Final to Initial Energy	.9465	.9495	.9525	.9553	.9577
Metric	**ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)**				
Radial Distance (ft)	3365	3464	3610	3675	3816
M_{final}	.3176	.3276	.3374	.3468	.3559
$Time_{final}$ (sec)	10.2	10.2	10.4	10.3	10.5
$Altitude_{final}$ (ft)	10291	10261	10224	10192	10154
Ratio of Final to Initial Energy	.9395	.9462	.9525	.9590	.9651

Metric	$\underline{\Delta W/S - \%}$ WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
	−10	**−5**	**0**	**5**	**10**
Radial Distance (ft)	3333	3462	3610	3729	3788
M_{final}	.3294	.3335	.3374	.3413	.3451
$Time_{final}$ (sec)	9.9	10.1	10.4	10.6	10.6
Altitude $_{final}$ (ft)	10396	10308	10224	10138	10065
Ratio of Final to Initial Energy	.9582	.9552	.9525	.9496	.9476

Table 25

Trajectory Results - Traj #3 - Max Effort Acceleration Δ100 KCAS
(ALT= 10000 ft, M = .2728, KCAS = 150)

Metric	ΔT/W - % WT=20000 lbs (Baseline T/W=1.66 @ sea level)				
	-10	-5	0	5	10
Down Range Distance(ft)	1613.4	1541.5	1467.5	1437.8	1360.5
Flight Path $Angle_{final}$ (deg)	-20.6	-19.7	-18.8	-18.3	-17.4
$Time_{final}$ (sec)	4.3	4.1	3.9	3.8	3.6
$Altitude_{final}$ (ft)	9646	9677	9707	9721	9749
Ratio of Final to Initial Energy	1.17	1.18	1.18	1.18	1.18
Metric	ΔT/W - % Thrust=const (Baseline T/W=1.66 @ sea level)				
Down Range Distance(ft)	1614.0	1541.9	1467.5	1437.4	1359.8
Flight Path $Angle_{final}$ (deg)	-20.6	-19.7	-18.8	-18.3	-17.4
$Time_{final}$ (sec)	4.3	4.1	3.9	3.8	3.6
$Altitude_{final}$ (ft)	9645	9677	9707	9721	9749
Ratio of Final to Initial Energy	1.18	1.18	1.18	1.18	1.18
Metric	ΔW/S - % WT=20000 lbs (Baseline W/S = 66.7 ft^2)				
Down Range Distance(ft)	1466.7	1467.1	1467.5	1467.9	1468.3
Flight Path $Angle_{final}$ (deg)	-18.8	-18.8	-18.8	-18.8	-18.8
$Time_{final}$ (sec)	3.9	3.9	3.9	3.9	3.9
$Altitude_{final}$ (ft)	9707	9707	9707	9707	9707
Ratio of Final to Initial Energy	1.18	1.18	1.18	1.18	1.18

Metric	$\Delta W/S$ - % WT = 20000 lbs (Baseline W/S = 66.7 ft^2)				
	-10	**-5**	**0**	**5**	**10**
Down Range Distance(ft)	1362.9	1438.2	1467.5	1542.8	1572.5
Flight Path $Angle_{final}$ (deg)	-17.4	-18.3	-18.8	-19.7	-20.2
$Time_{final}$ (sec)	3.6	3.8	3.9	4.1	4.2
Altitude $_{final}$ (ft)	9749	9721	9707	9677	9662
Ratio of Final to Initial Energy	1.18	1.18	1.18	1.18	1.18

Table 26

Trajectory Results - Traj #1 - Vertical Loop (ALT = 10000 ft, M = 0.8)

Metric	ΔG-onset - % (Baseline G-onset = 10g/sec) WT = 20000 lbs				
	-50	-25	0	25	50
Down Range Distance (ft)	2450.4	2064.1	1869.4	1762.0	1673.8
M_{final}	.4439	.4349	.4305	.4278	.4267
$Time_{mid}$ (sec)	9.0	8.7	8.5	8.4	8.3
$Altitude_{mid}$ (ft)	13245	13126	13071	13041	13020
Ratio of Mid to Initial Energy	.7481	.7371	.7313	.7282	.7258

Table 27

Trajectory Results - Traj #2 - Scissors Maneuver (ALT = 10000 ft, M = 0.4)

Metric	ΔRoll Rate - % (Baseline Roll Rate = 80 deg/sec) WT = 20000 lbs				
	-50	-25	0	25	50
Radial Distance (ft)	3801	3711	3610	3505	3462
M_{final}	.3055	.3293	.3374	.3434	.3472
$Time_{final}$ (sec)	12.2	11.0	10.4	9.9	9.7
$Altitude_{final}$ (ft)	10838	10390	10224	10106	10034
Ratio of Final to Initial Energy	.9709	.9576	.9525	.9493	.9474

Table 28

Trajectory Results - Traj #3 - Max Effort Acceleration Δ100 KCAS (ALT = 10000 ft, M = .2728, KCAS = 150)

Metric	ΔG-onset - % (Baseline G-onset = -2g/sec) WT = 20000 lbs				
	-50	-25	0	25	50
Down Range Distance(ft)	2163.8	1914.6	1809.0	1734.1	1699.9
Flight Path $Angle_{final}$ (deg)	-3.8	-8.7	-11.4	-12.9	-14.0
$Time_{final}$ (sec)	5.8	5.1	4.8	4.6	4.5
Altitude $_{final}$ (ft)	10178	10000	9916	9870	9835
Ratio of Final to Initial Energy	1.23	1.21	1.20	1.19	1.19
Metric	ΔPower Transition Time - % (Baseline Transition Time = 4 sec) WT = 20000 lbs				
Down Range Distance(ft)	1966.2	2022.1	2128.5	2194.2	2265.3
Flight Path $Angle_{final}$ (deg)	-16.8	-19.0	-21.3	-23.2	-25.0
$Time_{final}$ (sec)	5.5	5.8	6.2	6.5	6.8
Altitude $_{final}$ (ft)	9777	9724	9656	9603	9550
Ratio of Final to Initial Energy	1.19	1.18	1.18	1.17	1.16

Table 29

Eidetics Agility Metrics For Traj #1
(ALT = 10000 ft, M = 0.8)

Metric	ΔG-onset - % (Baseline G-onset = 10g/sec) WT = 20000 lbs				
	-50	**-25**	**0**	**25**	**50**
Avg Pitch Rate (for 1 sec)	16.1	23.7	29.5	31.7	33.2
Pitch Agility (time to 30 deg)	1.863	1.266	1.017	.9464	.9036
Avg Pitch Rate (for 5 sec)	23.9	25.6	26.4	26.9	27.2
Pitch Agility (time to 30 deg)	1.255	1.171	1.136	1.116	1.104

Table 30

Eidetics Agility Metrics For Traj #2
(ALT = 10000 ft, M = 0.4)

Metric	ΔG-onset - % (Baseline Roll Rate = 80 deg/sec) Turn Rate = 16.2 deg/sec, WT = 20000 lbs				
	-50	**-25**	**0**	**25**	**50**
Time (sec) (roll to 90 deg)	2.25	1.50	1.125	.900	.750
Turn Agility (deg/sec^2)	7.2	10.8	14.4	18.0	21.6

Table 31

Eidetics Agility Metrics For Traj #3
(ALT = 10000 ft, M = 0.2728)

Metric	ΔG–onset – % (Baseline G–onset = –2g/sec) WT = 20000 lbs				
	–50	**–25**	**0**	**25**	**50**
Avg Pitch Rate (for 1 sec)	–6.4	–14.5	–20.7	–25.0	–29.3
Pitch Agility (time to 30 deg)	4.688	2.069	1.449	1.200	1.024
Avg Pitch Rate (for 5 sec)	–6.12	–7.66	–8.42	–8.86	–9.16
Pitch Agility (time to 30 deg)	4.902	3.916	3.563	3.386	3.275

Table 32

Eidetics Agility Metrics For Traj #3
(ALT = 10000 ft, M = 0.2728)

Metric	ΔPower Rate – % (Baseline Transition Time = 4 sec) ΔPs = 586.4 ft/sec, WT = 20000 lbs				
	–50	**–25**	**0**	**25**	**50**
Transition Time (sec) (Ps_{max} to Ps_{min})	2	3	4	5	6
Axial Agility (ft/sec^2)	293.20	195.47	146.60	117.28	97.73

Table 33

Trajectory Results – Traj #3 – Max Effort Acceleration Δ100 KCAS
(ALT = 10000 ft, M = .2728, KCAS = 150)

Metric	ΔG–onset – % (Baseline G–onset = –2g/sec) WT = 20000 lbs				
	-50	-25	0	25	50
Down Range Distance(ft)	2163.8	1914.6	1809.0	1734.1	1699.9
Flight Path $Angle_{final}$ (deg)	-3.8	-8.7	-11.4	-12.9	-14.0
$Time_{final}$ (sec)	5.8	5.1	4.8	4.6	4.5
$Altitude_{final}$ (ft)	10178	10000	9916	9870	9835
Ratio of Final to Initial Energy	1.23	1.21	1.20	1.19	1.19
Metric	**ΔPower Transition Time – % (Baseline Transition Time = 4 sec) WT = 20000 lbs**				
Down Range Distance(ft)	1966.2	2022.1	2128.5	2194.2	2265.3
Flight Path $Angle_{final}$ (deg)	-16.8	-19.0	-21.3	-23.2	-25.0
$Time_{final}$ (sec)	5.5	5.8	6.2	6.5	6.8
$Altitude_{final}$ (ft)	9777	9724	9656	9603	9550
Ratio of Final to Initial Energy	1.19	1.18	1.18	1.17	1.16

Appendix C: Correlation Results

Legends for Figures 55 thru 89

Agility Metrics

1a - Herbst Axial
1b - Herbst Turn
1c - Herbst Pitch
2a - Eidetics Torsional
2b - Eidetics Axial
3a - Kalviste's DT
3b - Kalviste's V/Vc
3c - Kalviste's CCT
4 - Dorn's $A_{L.A.T.}$
5a - McAtee's Turn Rate
5b - McAtee's Bleed Rate
5c - McAtee's Accel Rate

T/W, W/S - Design Metric

Agility Metrics

Ep1 - Eidetics Pitch (1 sec avg)
Ep5 - Eidetics Pitch (5 sec avg)
Et - Eidetics Torsional
Ea - Eidetics Axial

Control Rates

Gon - G-onset Rate
Roll - Rate Rate
Pow - Power Rate

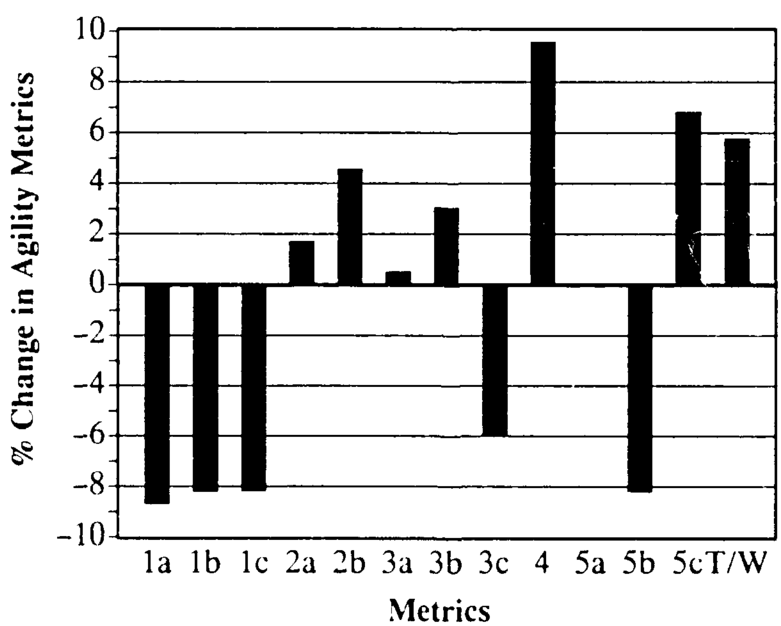


Figure 55. [Traj #1] -1% Change in Midpoint Time (T/W, WT=20000 lbs)

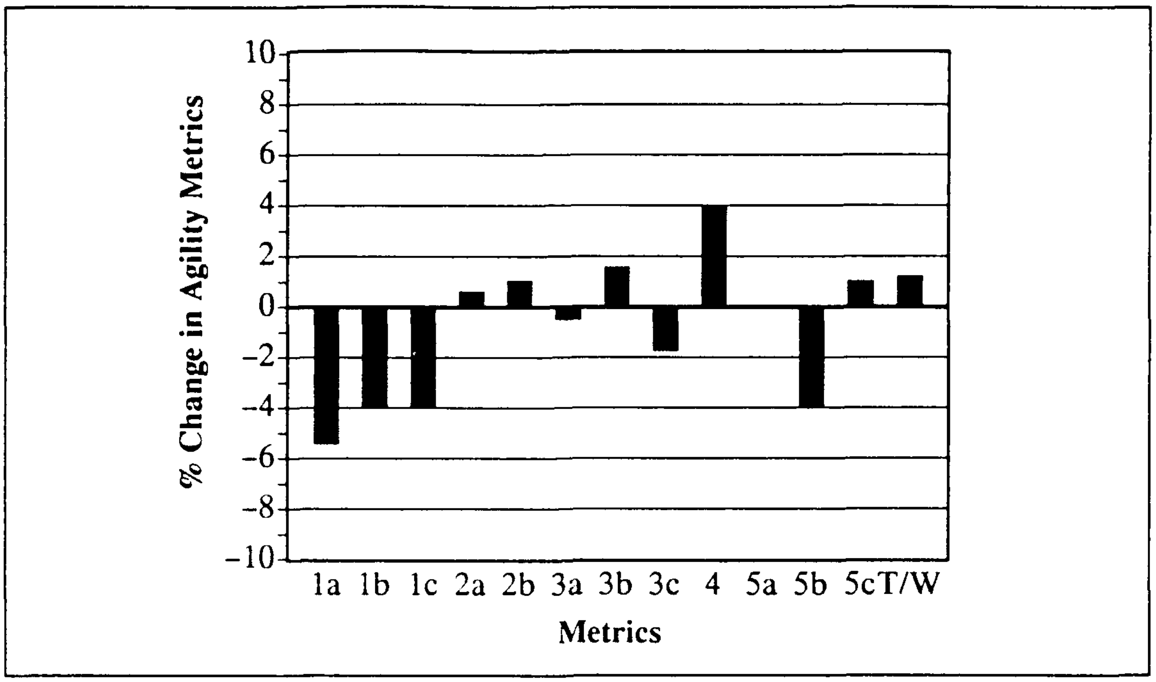


Figure 56. [Traj #1] -1% Change in Midpoint Time (T/W, Fn = const)

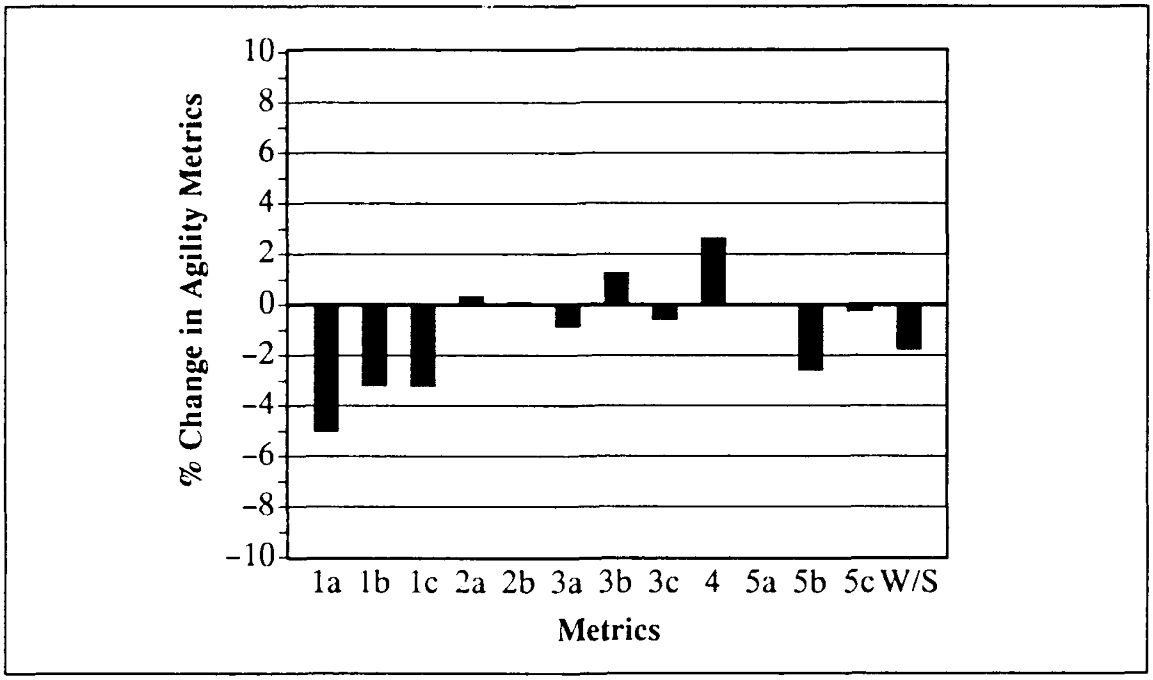


Figure 57. [Traj #1] -1% Change in Midpoint Time (W/S, WT = 20000 lbs)

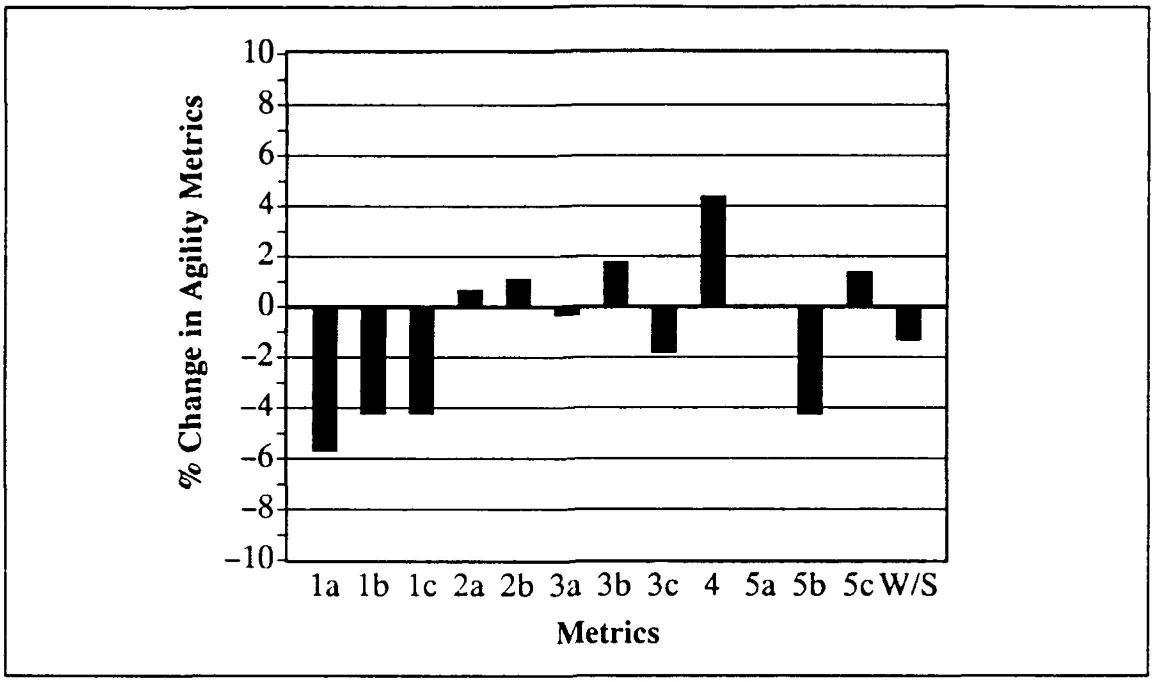


Figure 58. [Traj #1] -1% Change in Midpoint Time (W/S, S=300 ft^2)

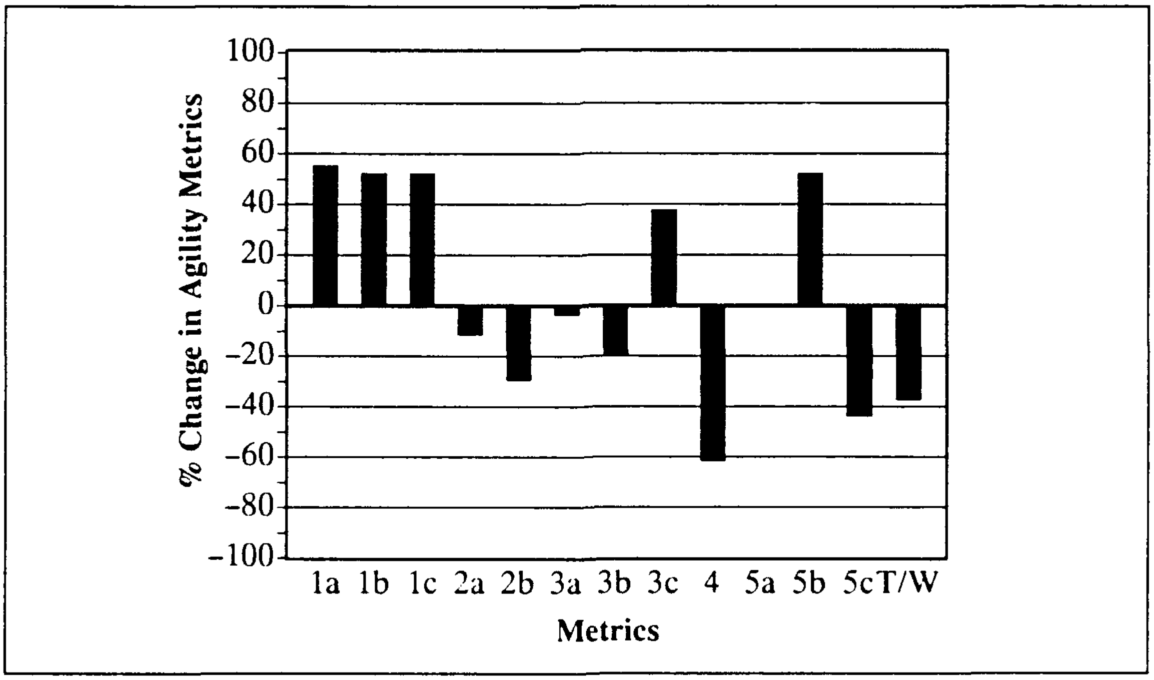


Figure 59. [Traj #1] -1% Change in Midpoint Altitude (T/W, WT=20000 lbs)

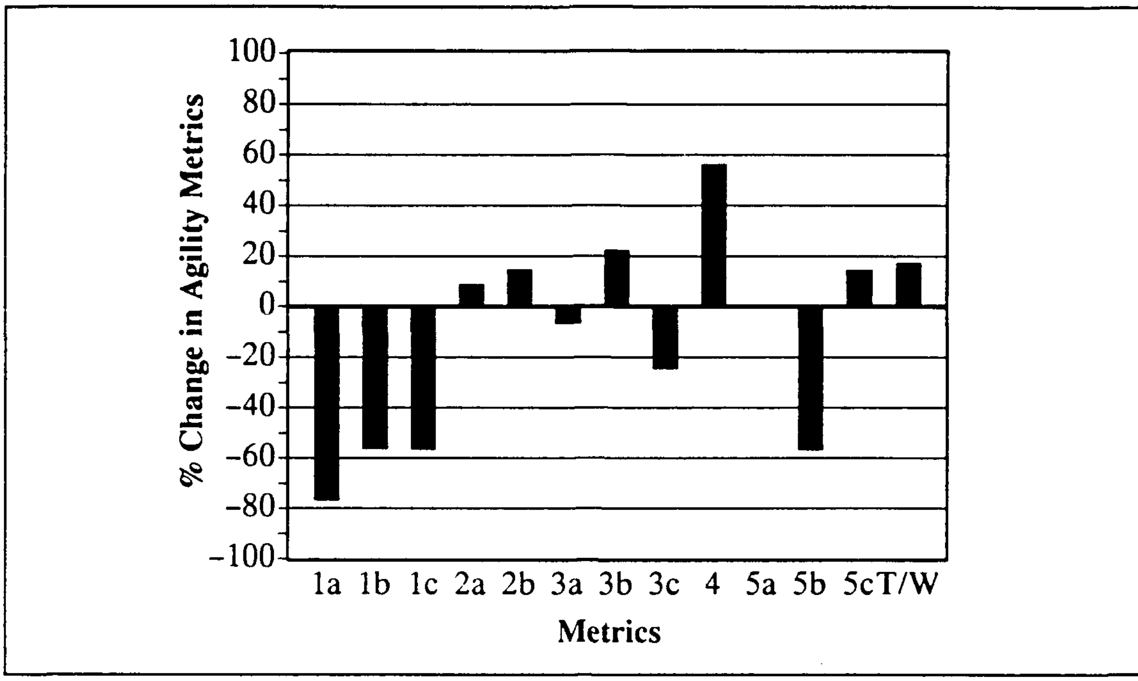


Figure 60. [Traj #1] -1% Change in Midpoint Altitude (T/W, Fn = const)

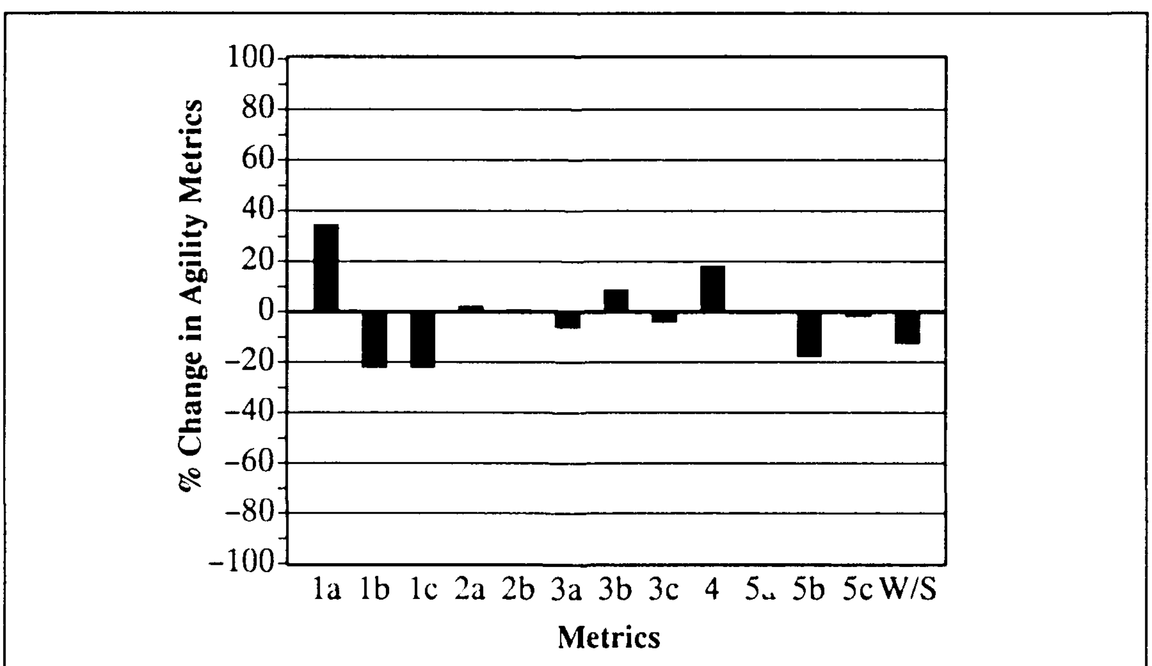


Figure 61. [Traj #1] -1% Change in Midpoint Altitude (W/S, WT = 20000 lbs)

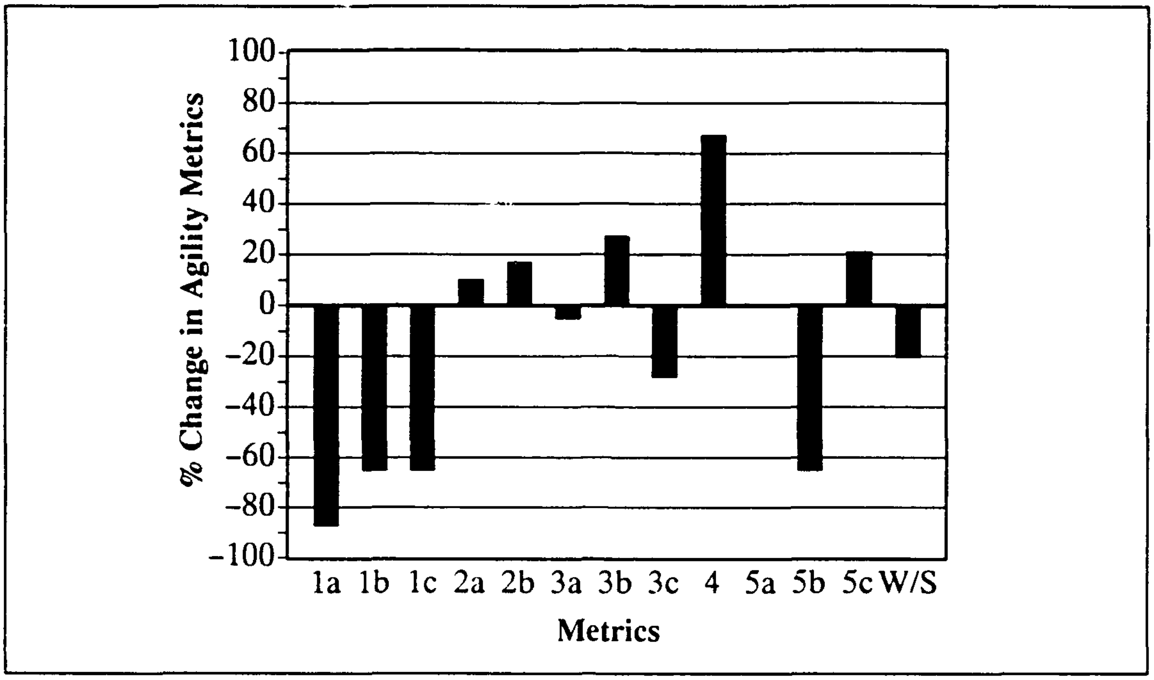


Figure 62. [Traj #1] –1% Change in Midpoint Altitude (W/S, S = 300 ft^2)

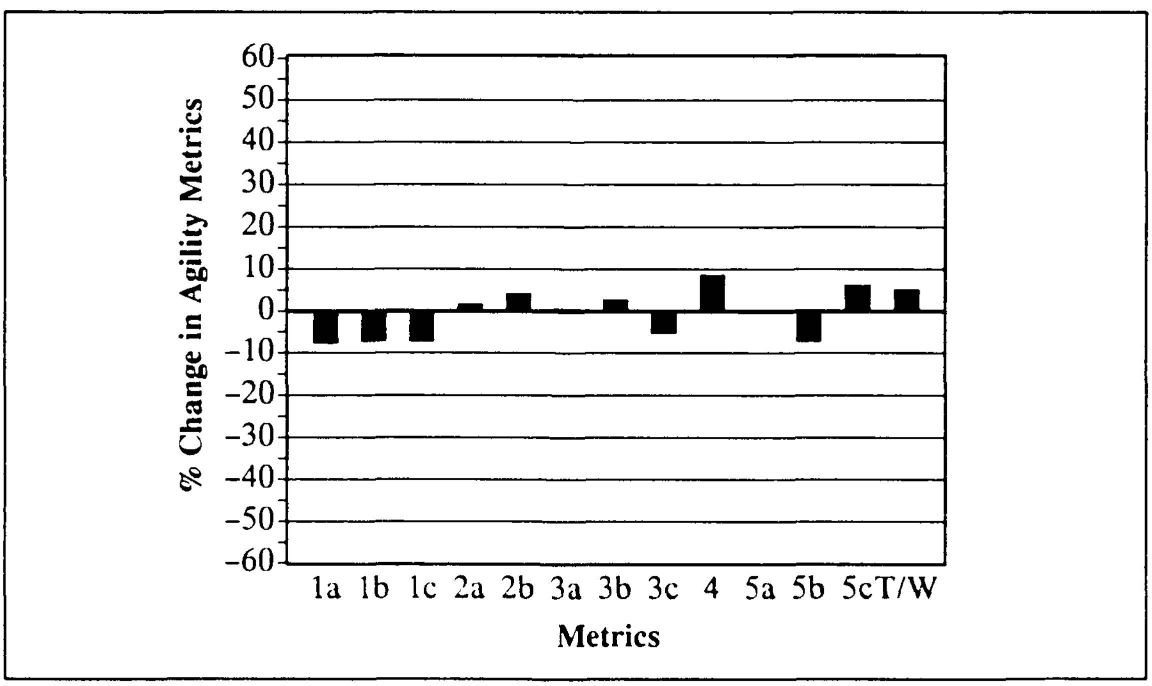


Figure 63. [Traj #1] –1% Change in Midpoint Energy Ratio (T/W, WT = 20000 lbs)

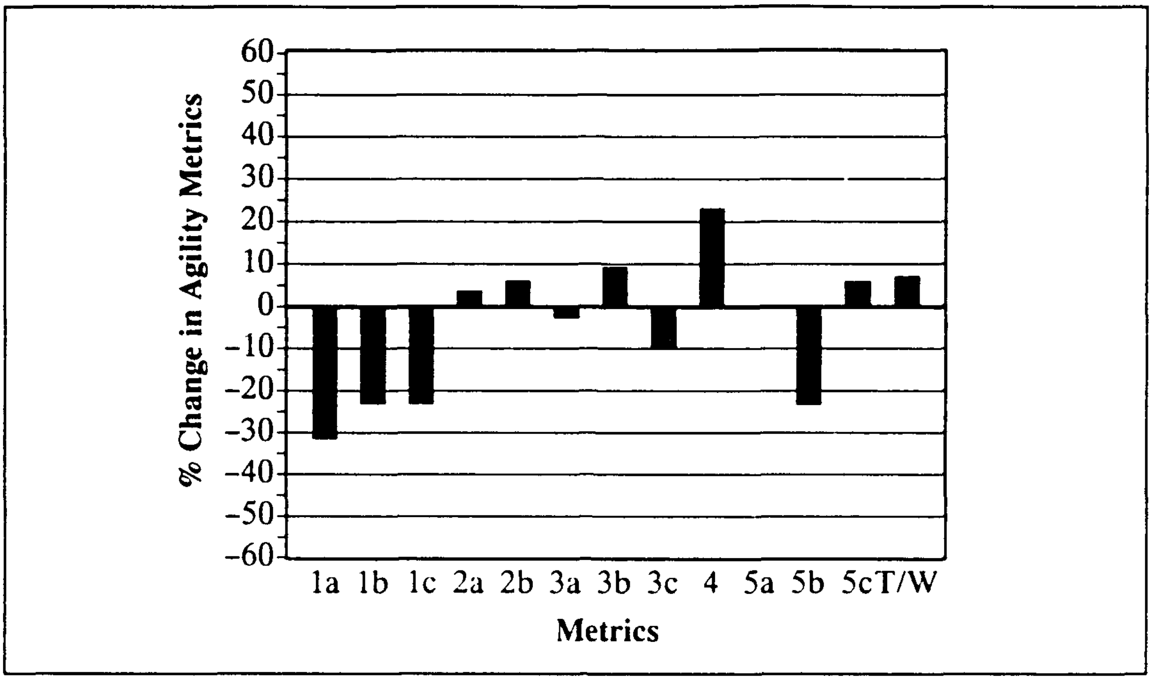


Figure 64. [Traj #1] -1% Change in Midpoint Energy Ratio (T/W, Fn = const)

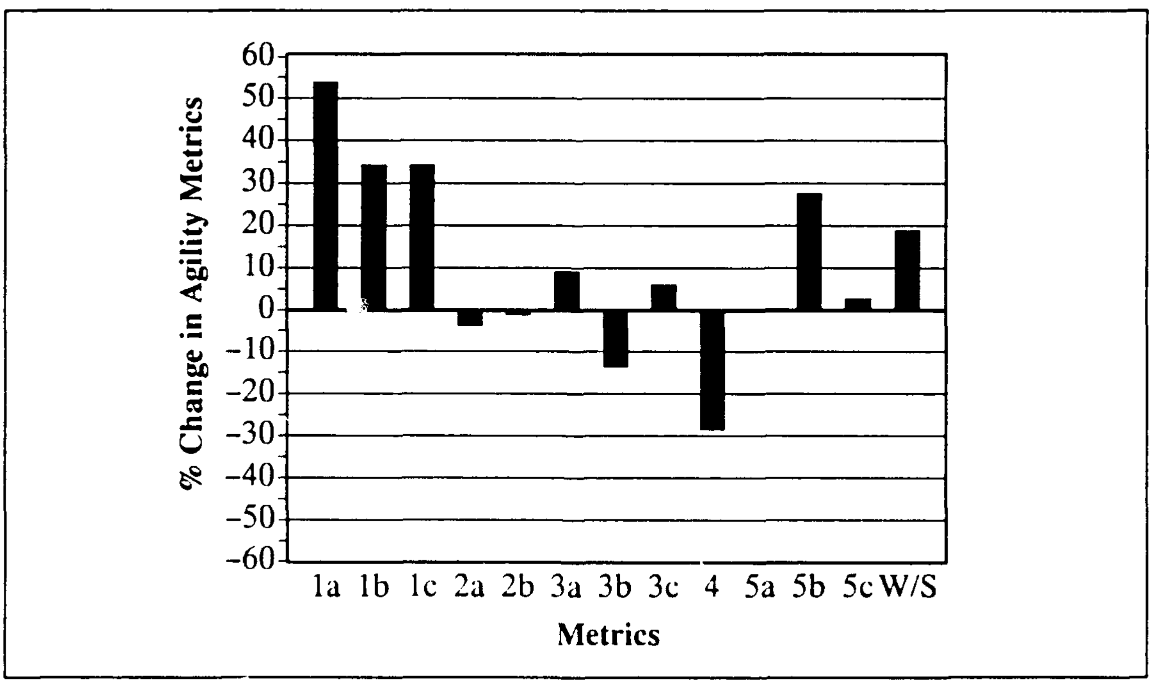


Figure 65. [Traj #1] -1% Change in Midpoint Energy Ratio (W/S, WT = 20000 lbs)

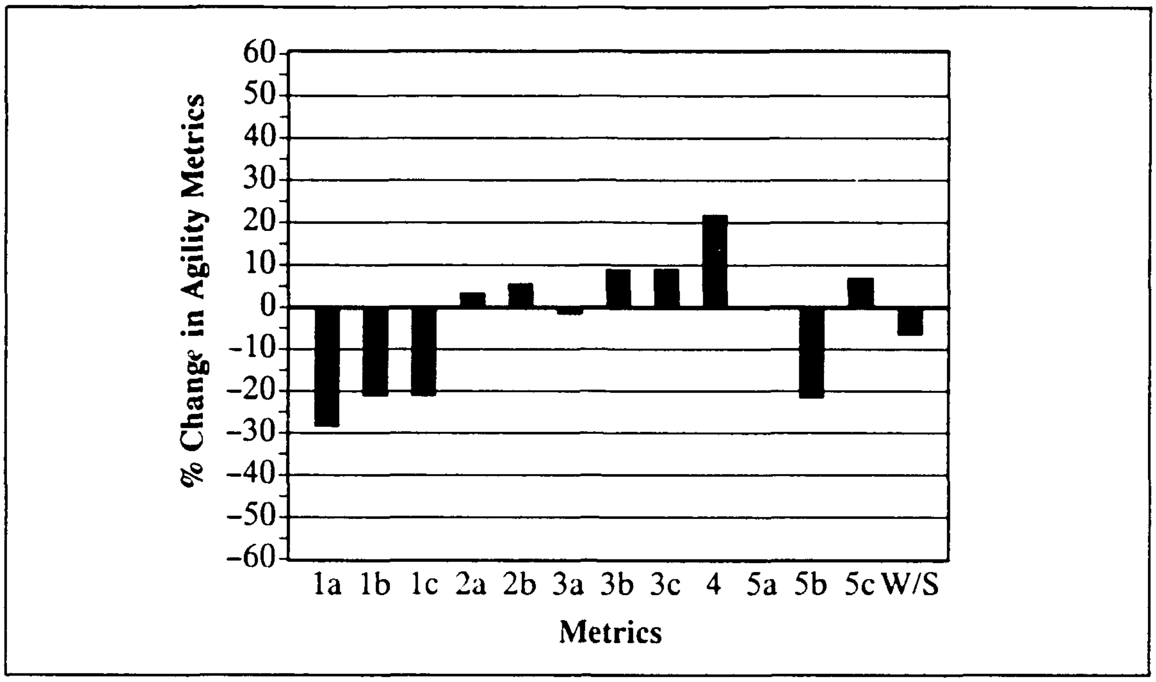


Figure 66. [Traj #1] -1% Change in Midpoint Energy Ratio (W/S, S=300 ft^2)

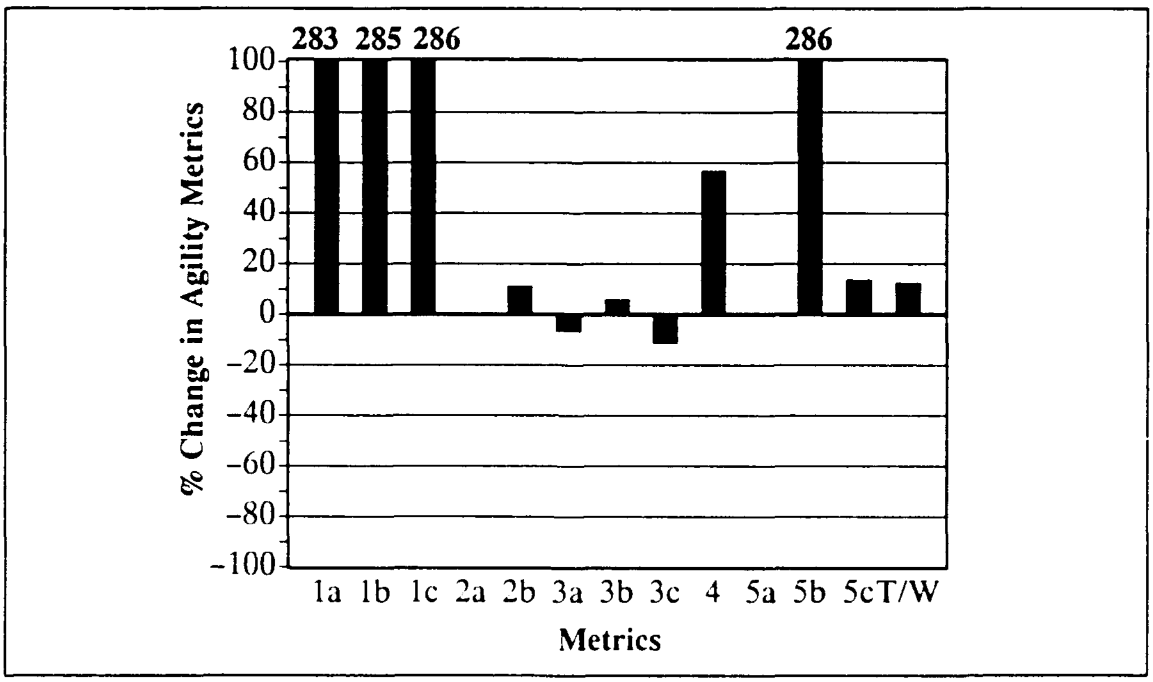


Figure 67. [Traj #2] -1% Change in Radial Distance (T/W, WT=20000 lbs)

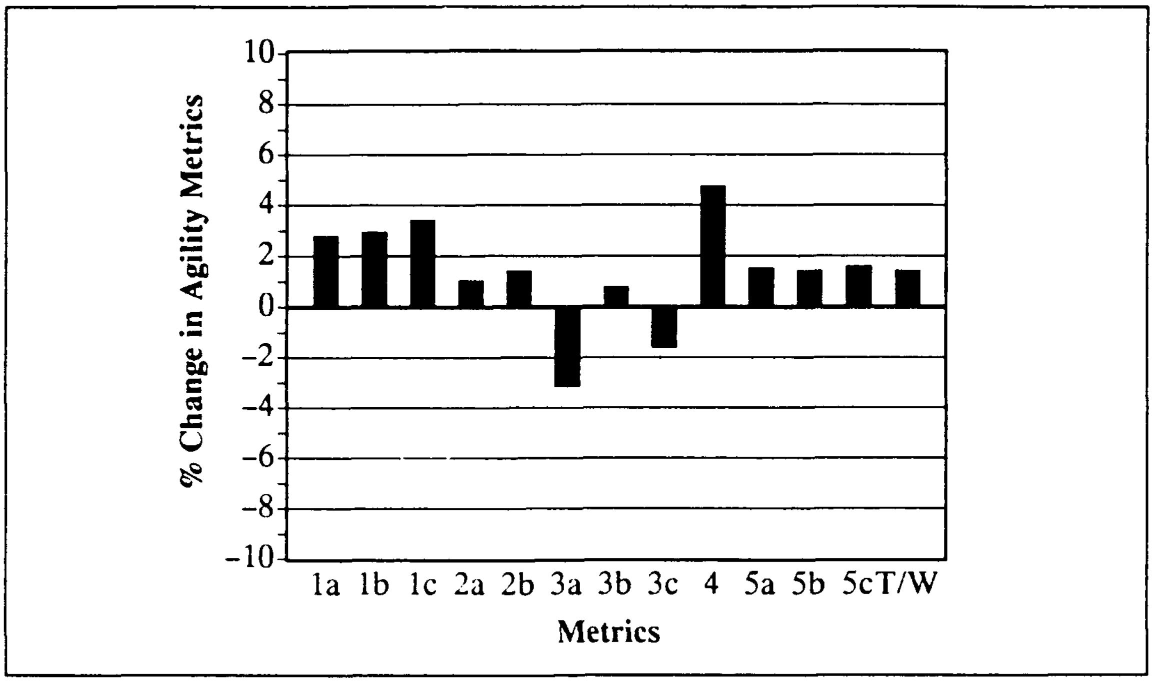


Figure 68. [Traj #2] -1% Change in Radial Distance (T/W, Fn = const)

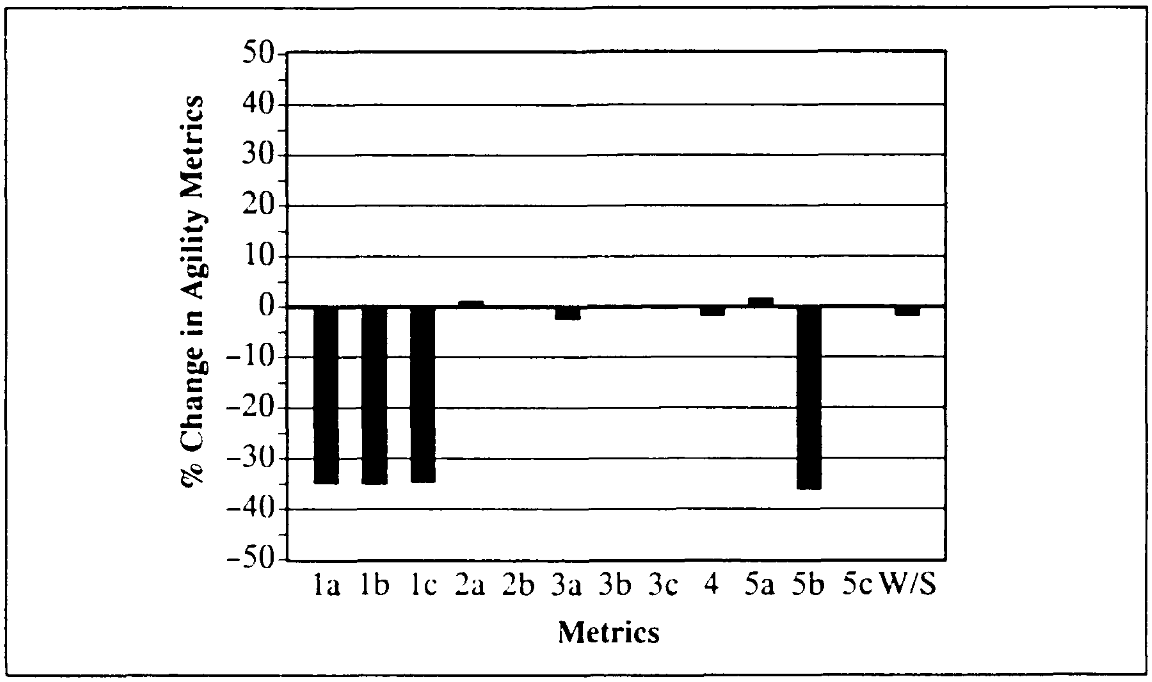


Figure 69. [Traj #2] -1% Change in Radial Distance (W/S, WT = 20000 lbs)

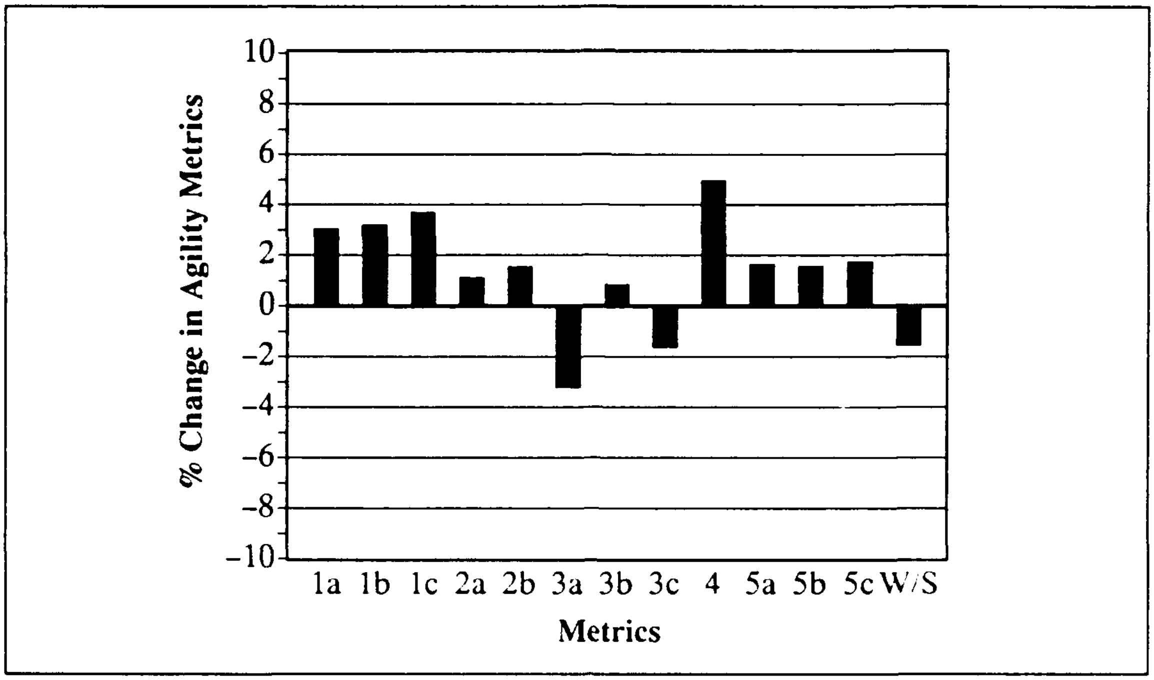


Figure 70. [Traj #2] -1% Change in Radial Distance (W/S, S = 300 ft^2)

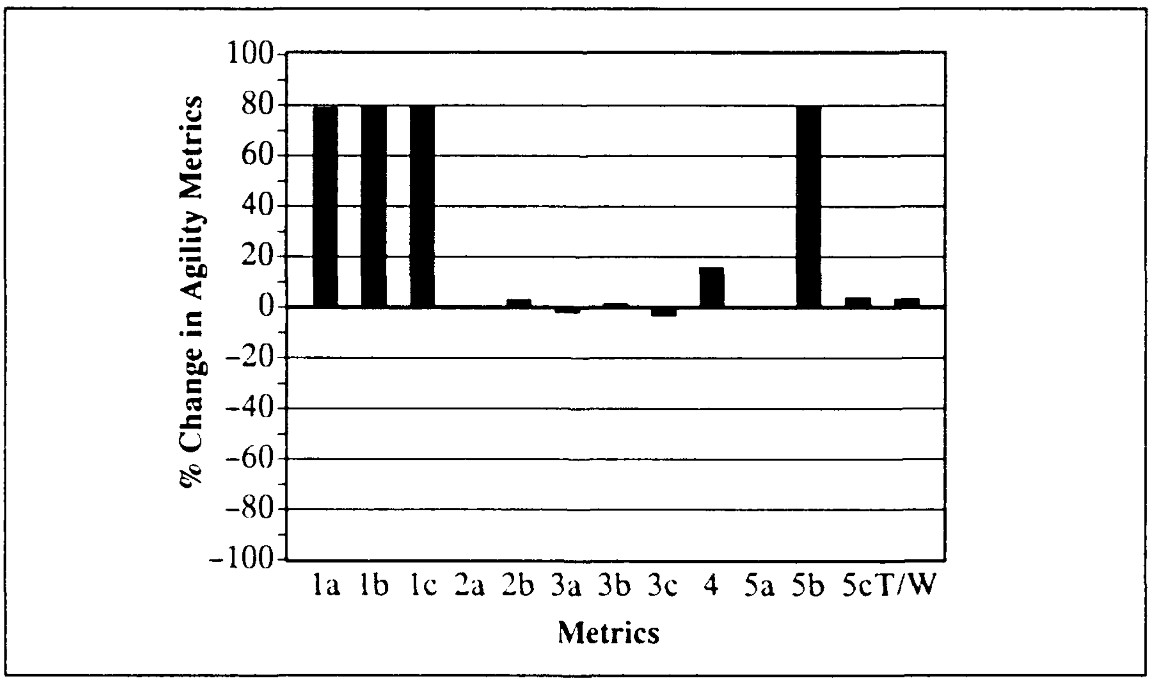


Figure 71. [Traj #2] -1% Change in Maneuver Time (T/W, WT = 20000 lbs)

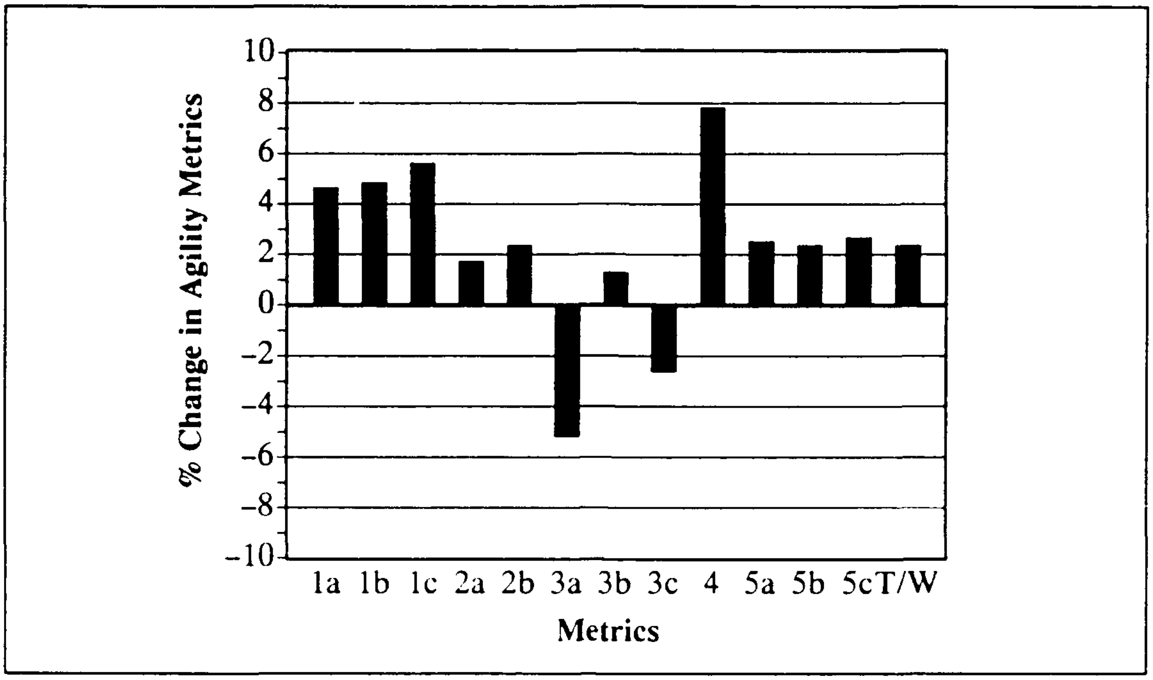


Figure 72. [Traj #2] -1% Change in Maneuver Time (T/W, Fn = const)

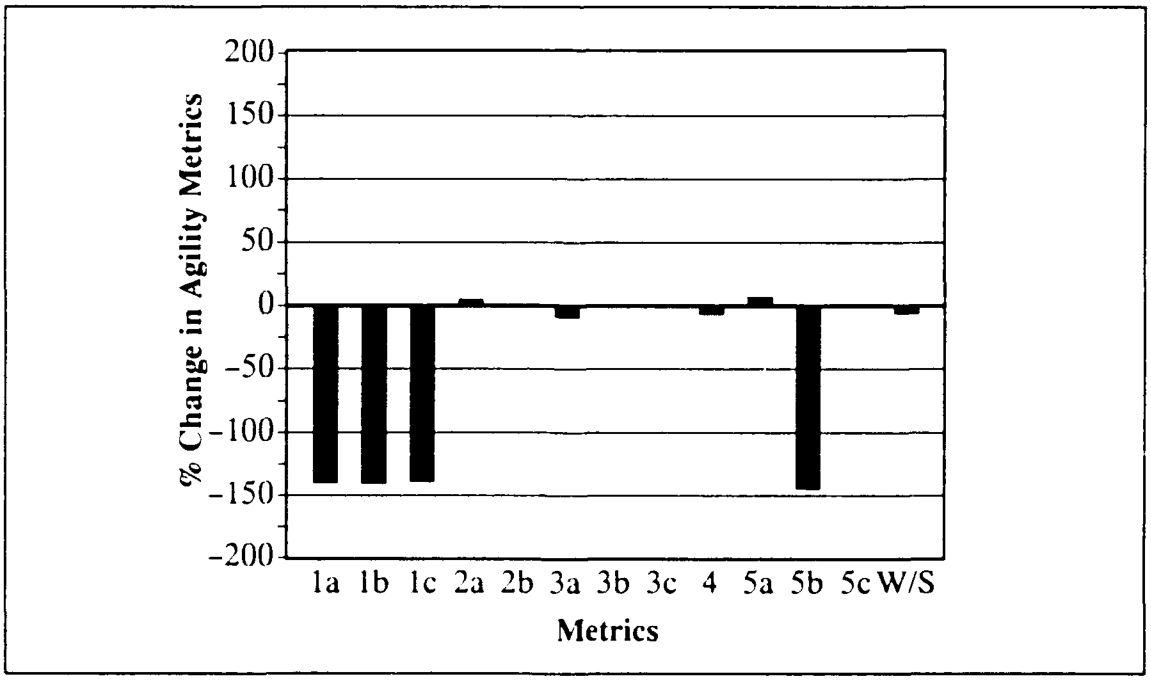


Figure 73. [Traj #2] -1% Change in Maneuver Time (W/S, WT = 20000 lbs)

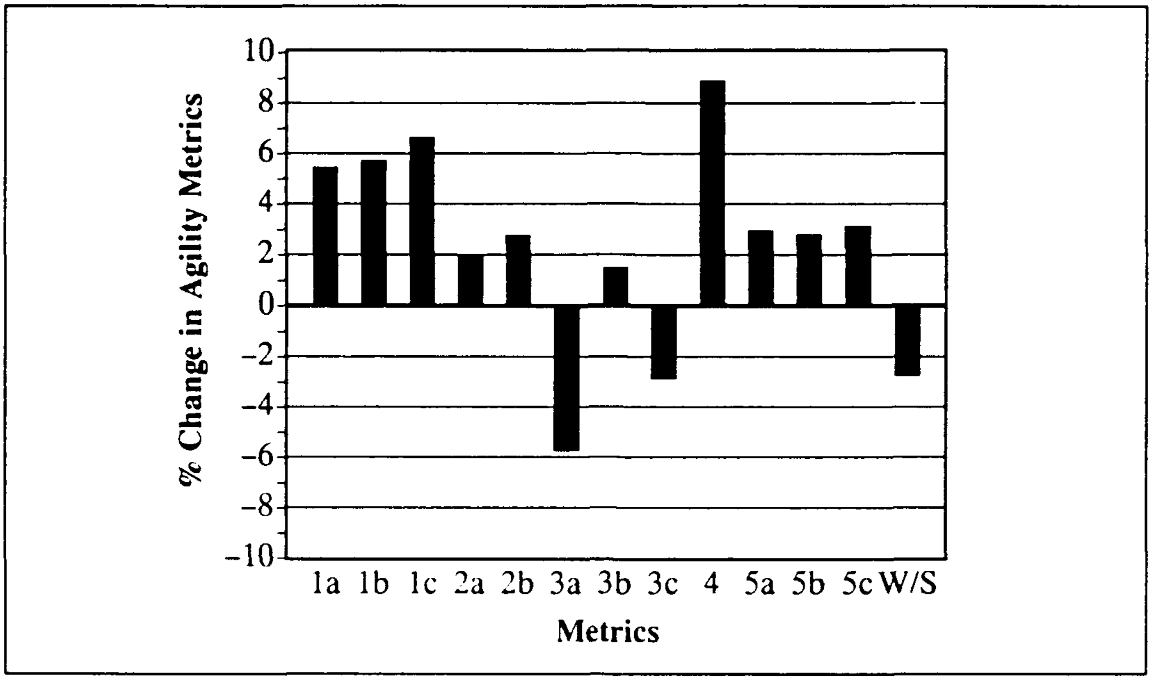


Figure 74. [Traj #2] -1% Change in Maneuver Time (W/S, S=300 ft^2)

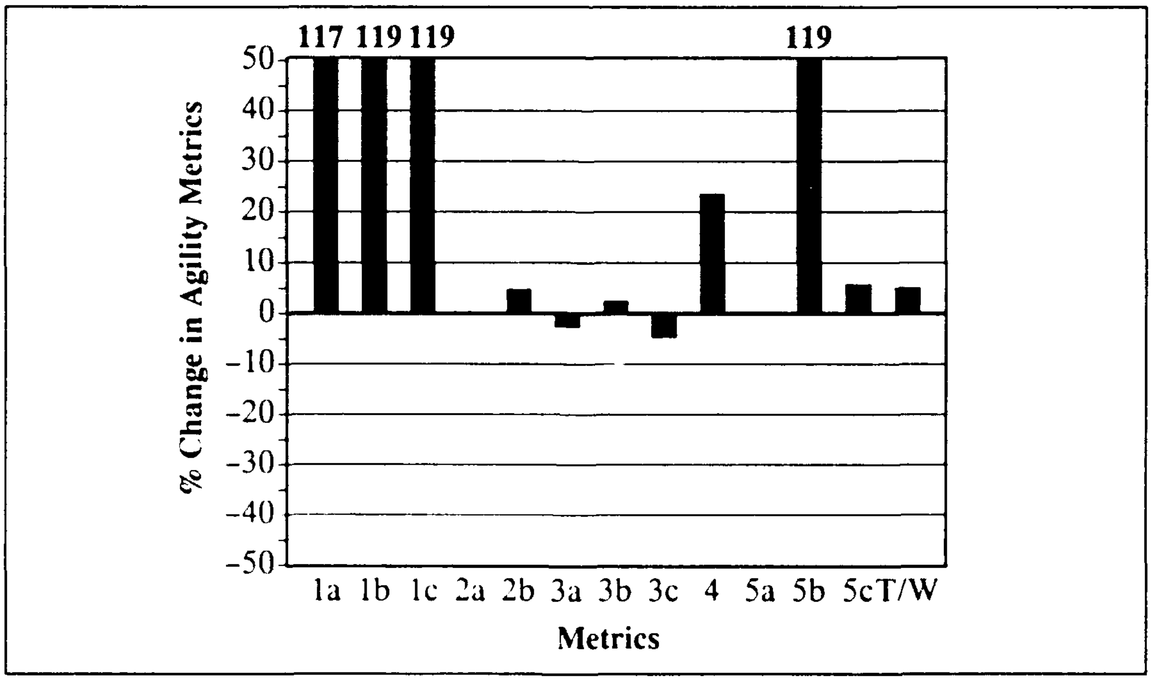


Figure 75. [Traj #2] 1% Change in Energy Ratio (T/W, WT=20000 lbs)

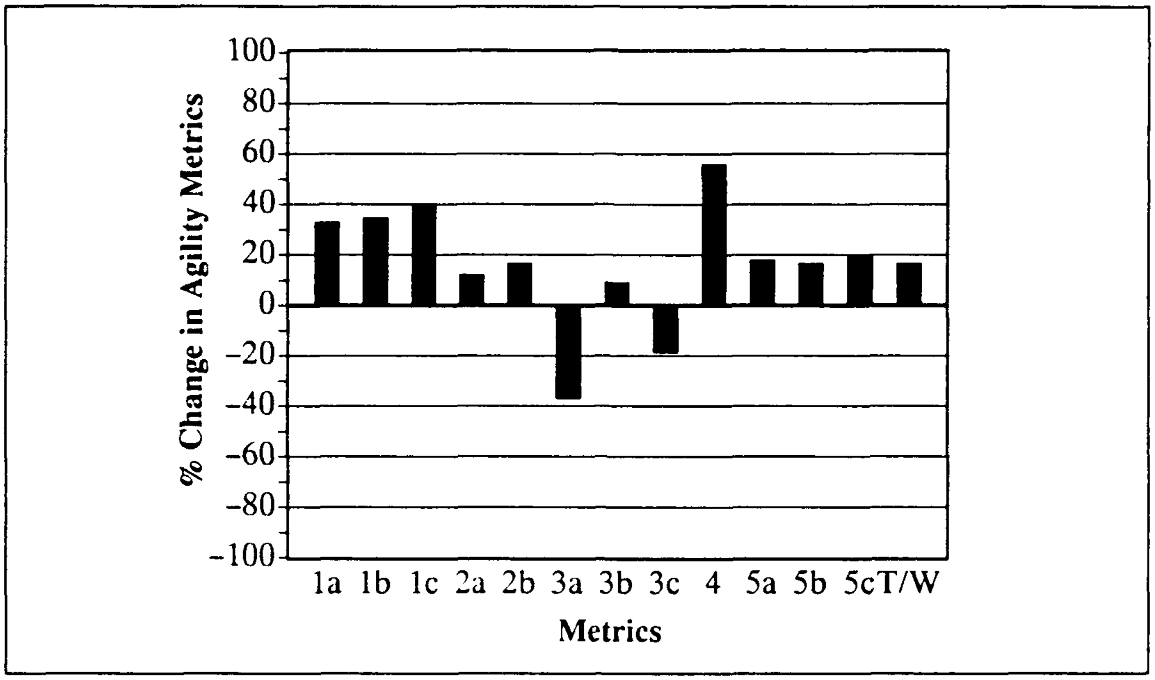


Figure 76. [Traj #2] 1% Change in Energy Ratio (T/W, Fn = const)

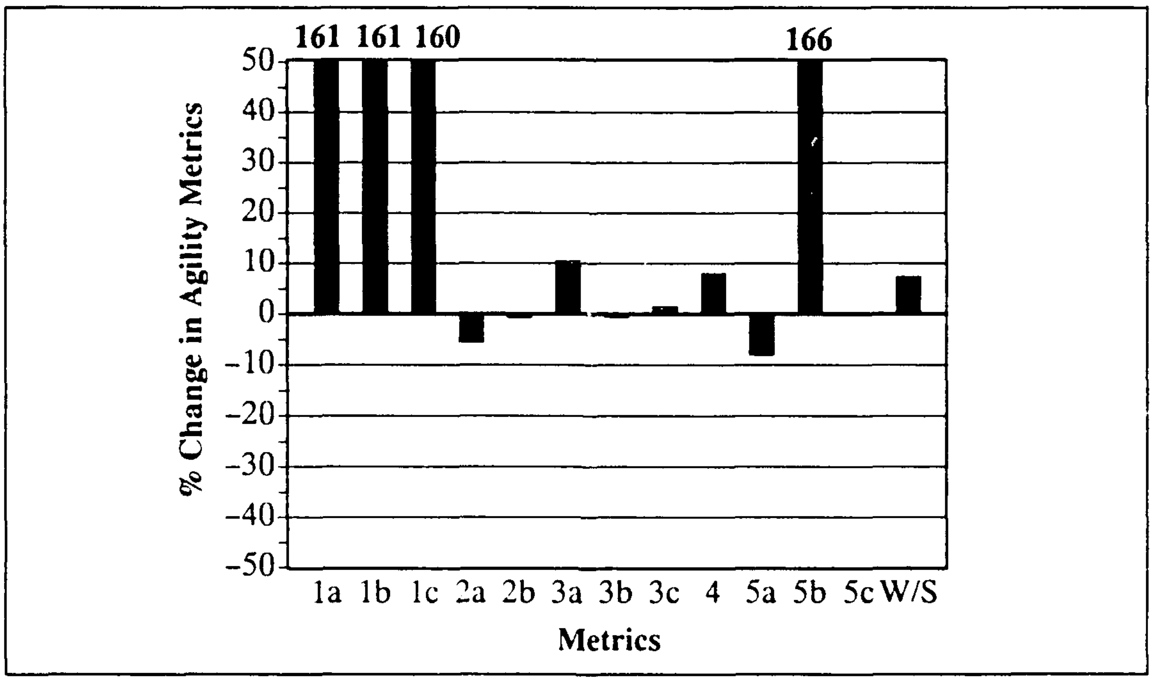


Figure 77. [Traj #2] 1% Change in Energy Ratio (W/S, WT = 20000 lbs)

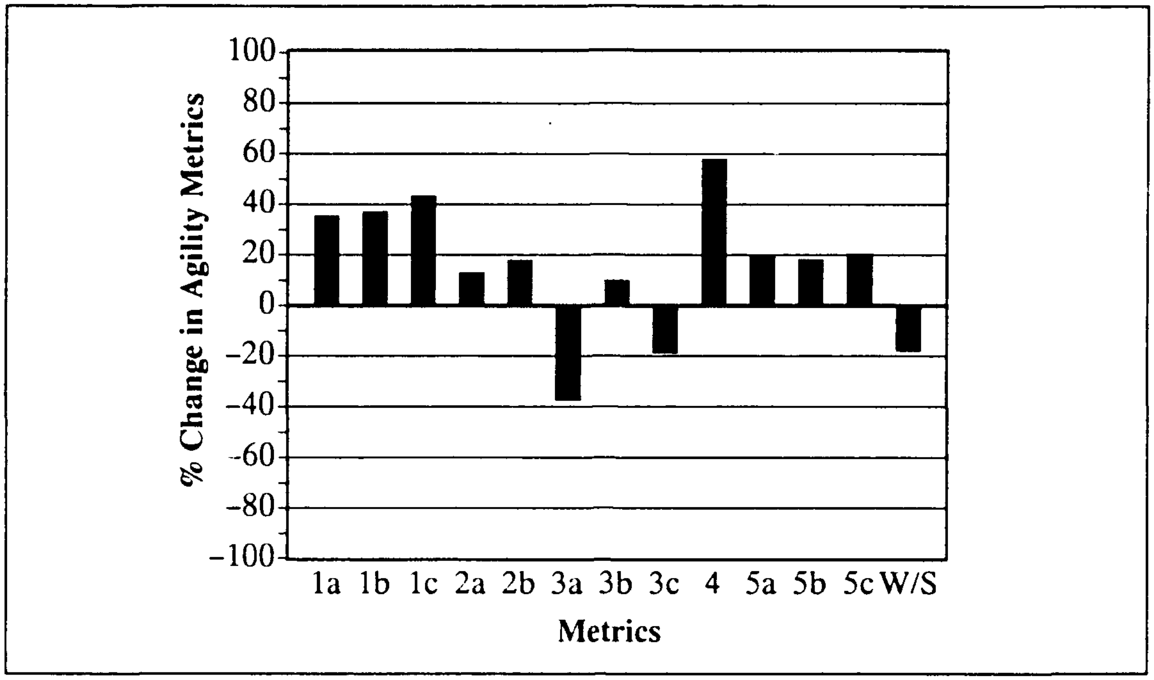


Figure 78. [Traj #2] 1% Change in Energy Ratio (W/S, S=300 ft^2)

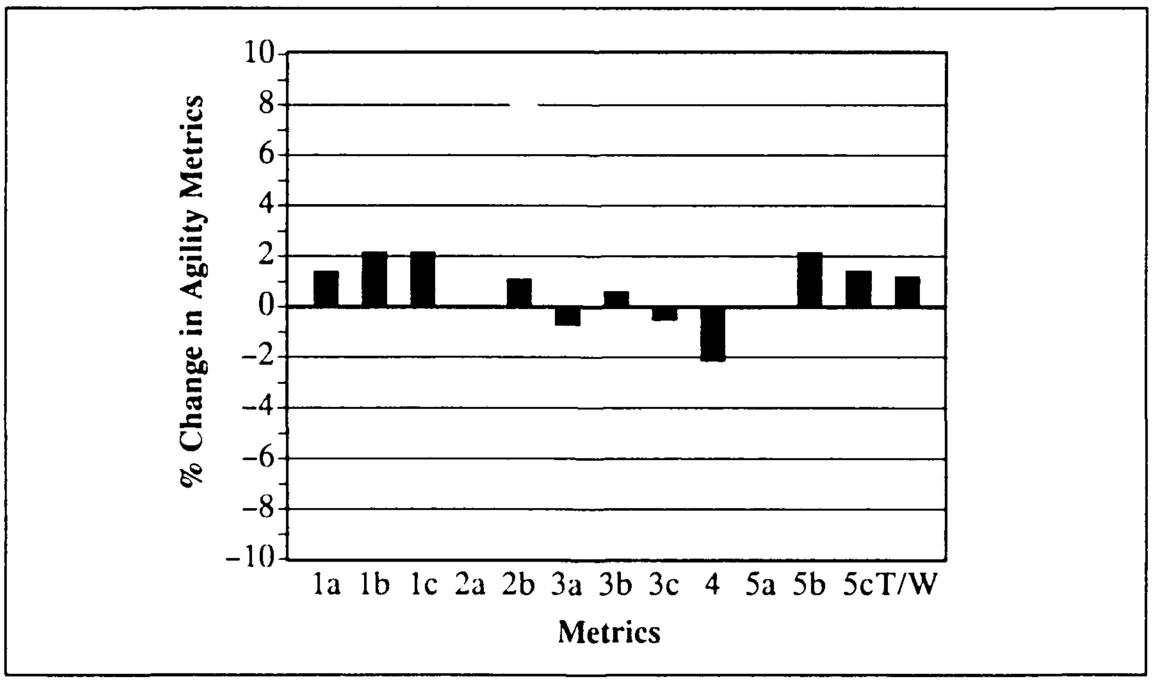


Figure 79. [Traj #3] -1% Change in Down Range Distance (T/W, WT=20000 lbs)

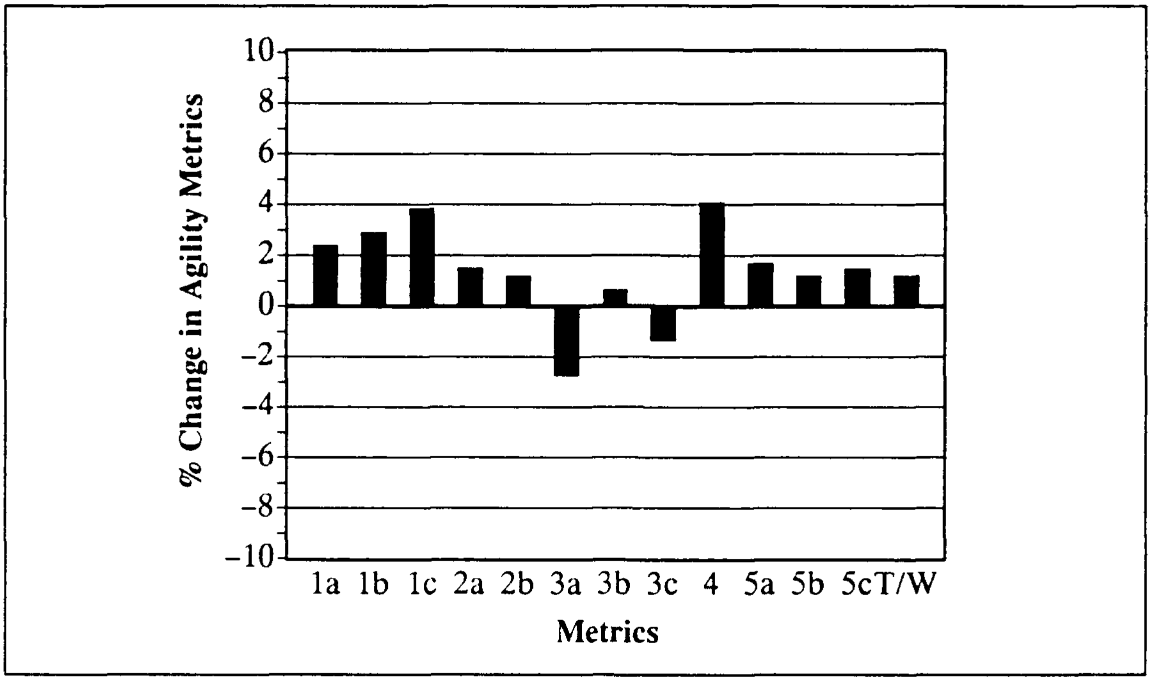


Figure 80. [Traj #3] -1% Change in Down Range Distance (T/W, Fn = const)

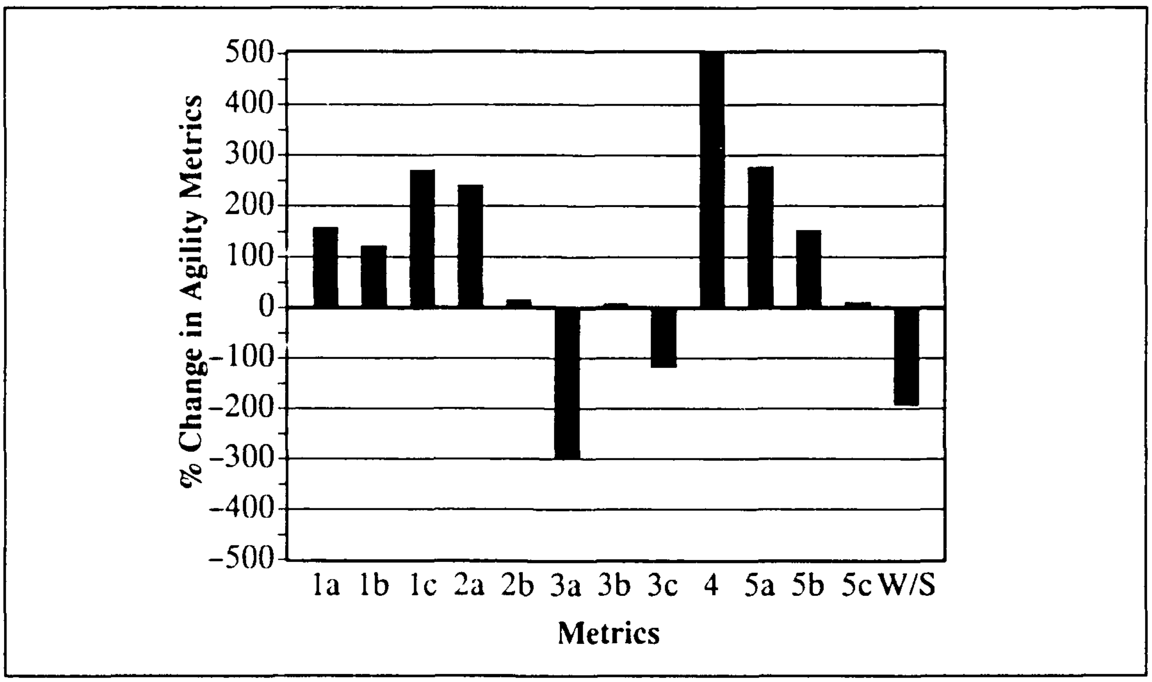


Figure 81. [Traj #3] -1% Change in Down Range Distance (W/S, WT = 20000 lbs)

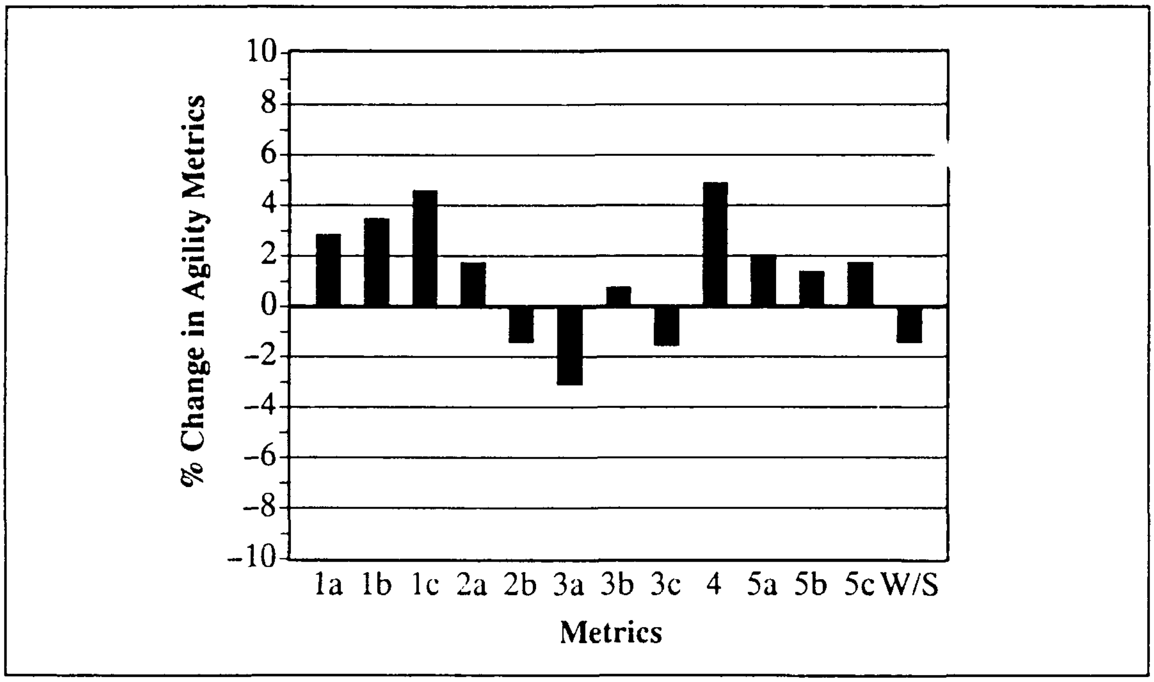


Figure 82. [Traj #3] -1% Change in Down Range Distance (W/S, S=300 ft^2)

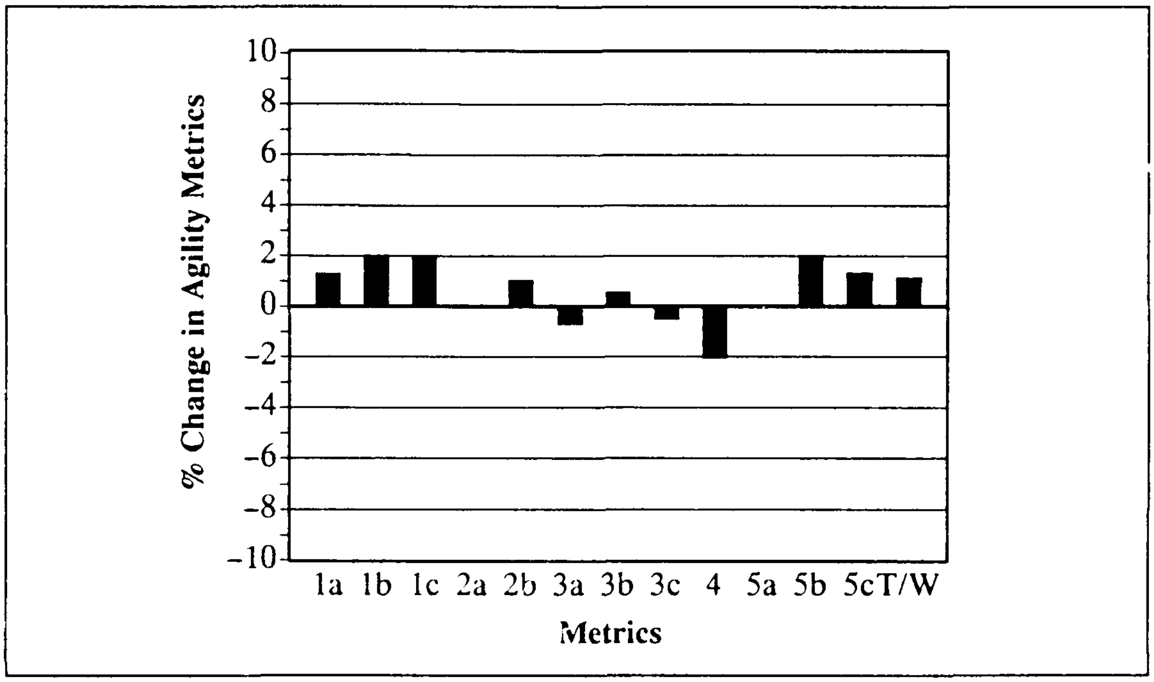


Figure 83. [Traj #3] -1% Change in Maneuver Time (T/W, WT=20000 lbs)

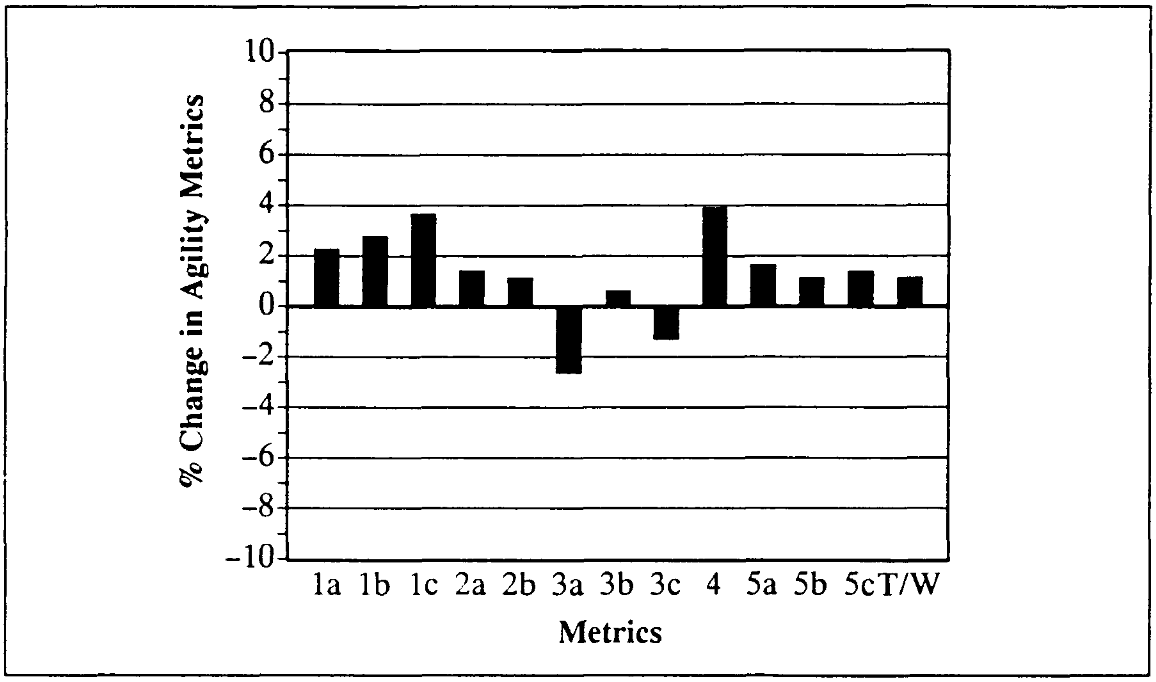


Figure 84. [Traj #3] –1% Change in Maneuver Time (T/W, Fn = const)

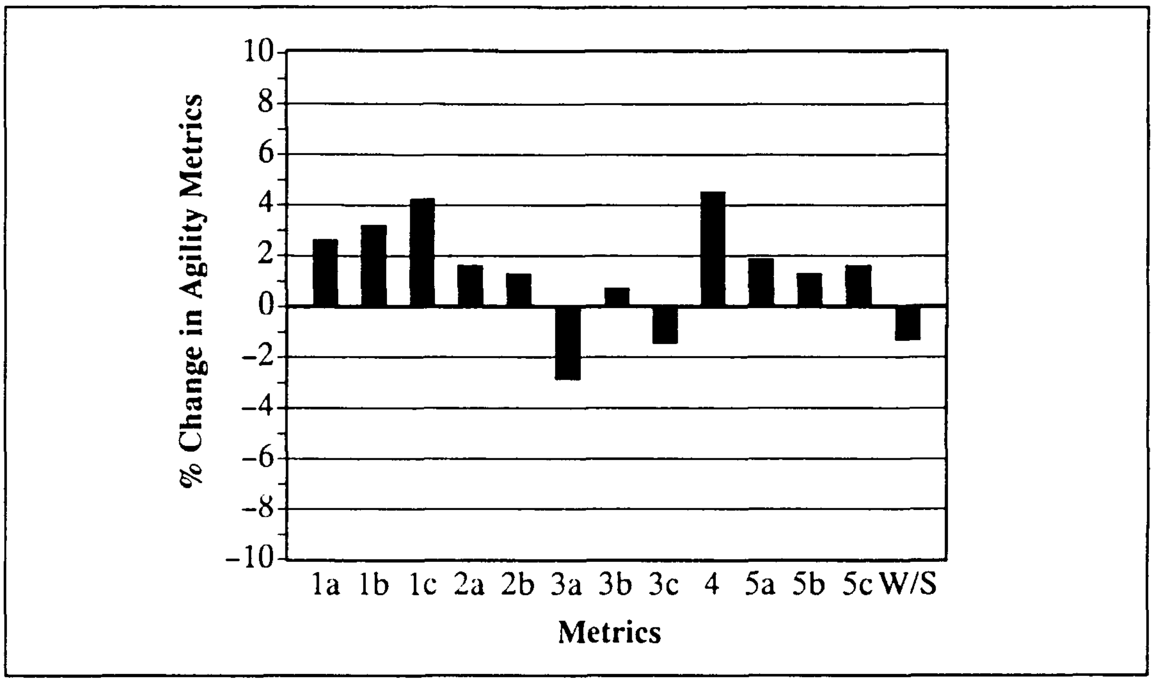


Figure 85. [Traj #3] –1% Change in Maneuver Time (W/S, S = 300 ft^2)

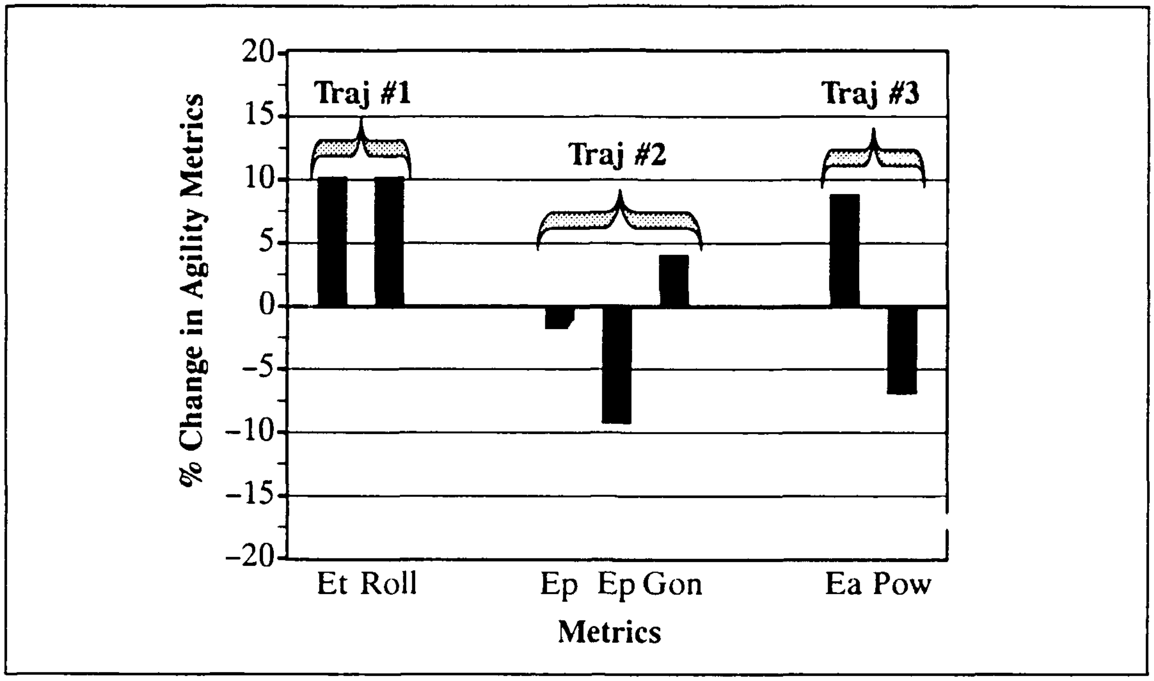


Figure 86. [Traj #1-3] -1% Change in Maneuver Distance

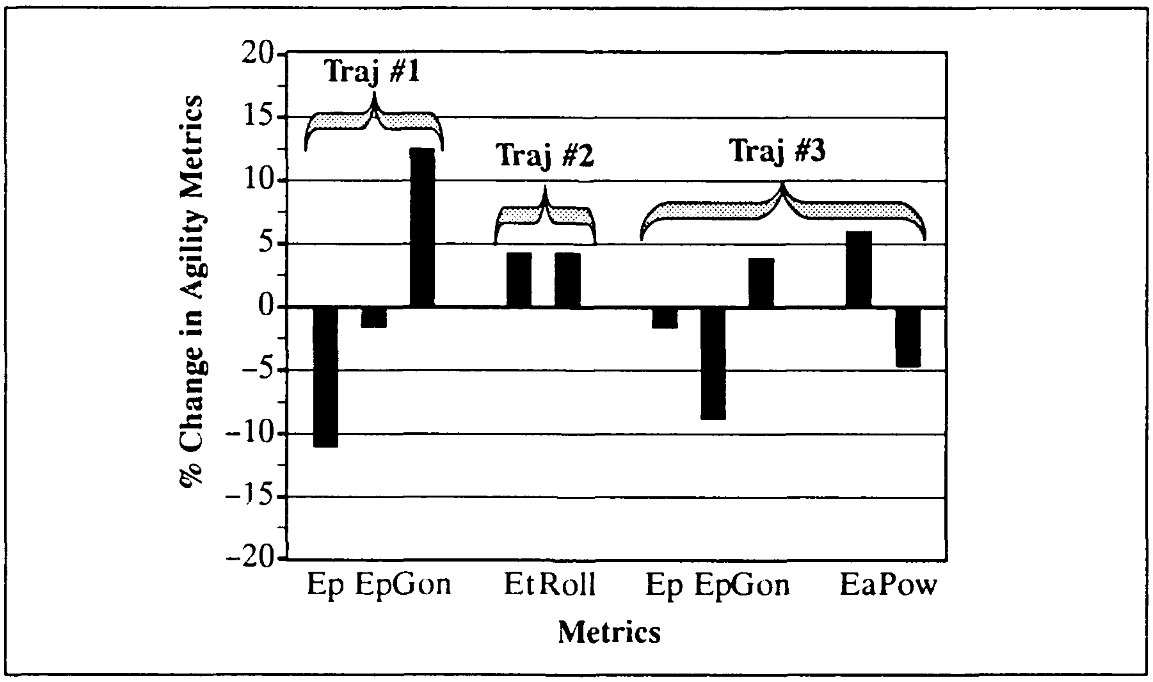


Figure 87. [Traj #1-3] -1% Change in Maneuver Time

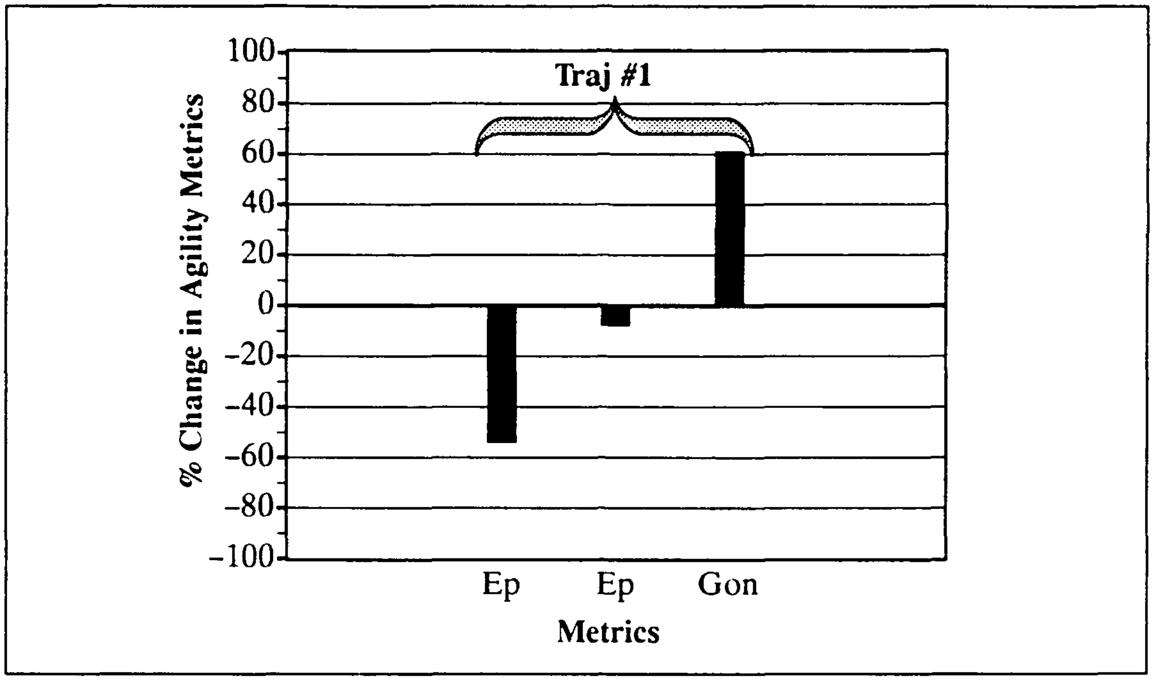


Figure 88. [Traj #1] -1% Change in Delta Altitude

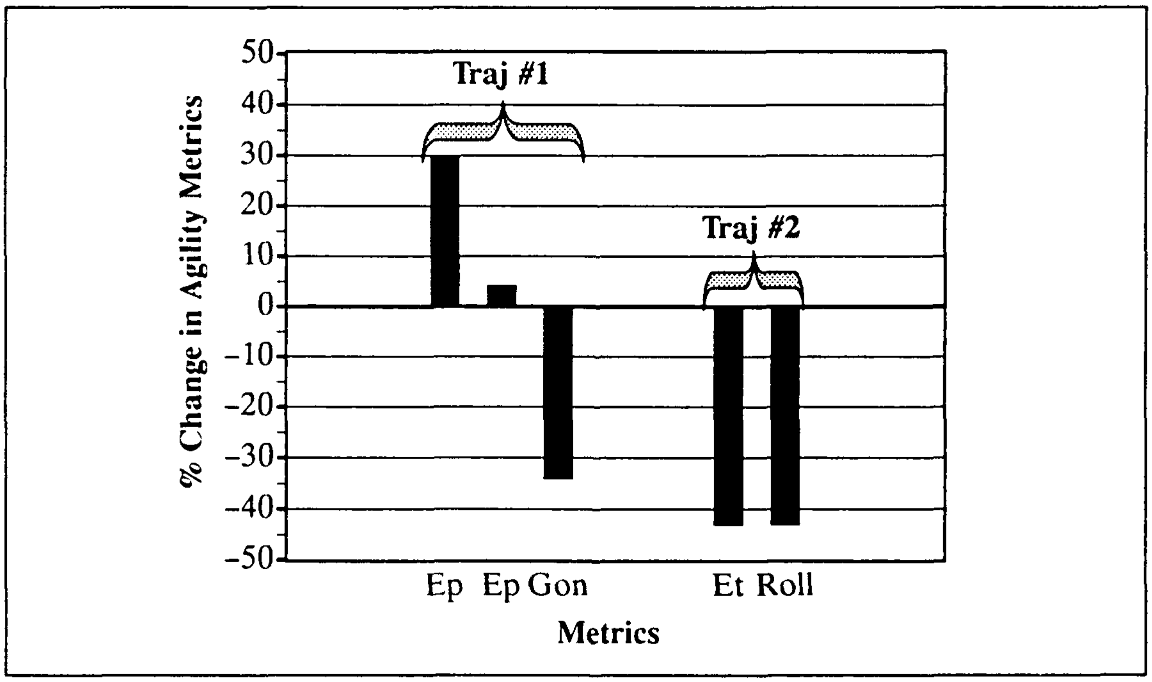


Figure 89. [Traj #1-2] 1% Change in Ratio of Final to Initial Energy

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